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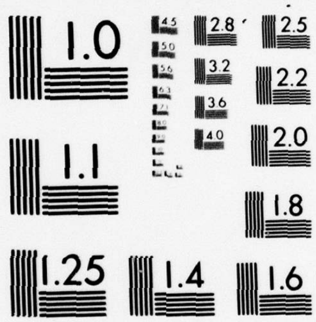


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# Technical Note

TN no. N-1540

**title:** SURVEY AND PRELIMINARY FEASIBILITY ASSESSMENT FOR RUNNING GEAR MODULE FOR A DEEP OCEAN WORK VEHICLE


**author:** H. G. Herrmann



**date:** January 1979

**sponsor:** Naval Facilities Engineering Command

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CIVIL ENGINEERING LABORATORY
NAVAL CONSTRUCTION BATTALION CENTER
Port Hueneme, California 93043


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## ABSTRACT

Background information impacting the technical feasibility of developing an active running gear system for use on a deep ocean vehicle is summarized along with preliminary conceptual configurations for such a system. Characteristics and available performance data on some 66 existing seafloor vehicles (none of which are designed for the environment or operating scenario/mission of interest to this study) are reviewed and summarized along with likely environmental conditions. It is concluded that either a rotor/screw or track running gear type will provide the best potential performance on the very weak and highly plastic cohesive soils to be encountered in the deep ocean. Draw bar pull forces of the order of 400 pounds are developable using an active running gear module which is light weight (possibly neutrally buoyant in some cases) is compatible with, and relies on, its host vehicle for power and control functions.

Potential areas of significant work capability enhancement using such an active running gear module are summarized along with identified technical deficiencies and plans for addressing/satisfying these.

## INTRODUCTION

This Technical Memorandum summarizes the original survey of background information and feasibility assessment, including the preliminary conceptualization and feasibility studies, completed as a first step in the development effort of an active running gear module for use in conjunction with an existing, undetermined seafloor work vehicle in the deep ocean environment. A subsequent Technical Memorandum summarizes a series of more detailed studies which provided information for refining the concept and defining more precisely technical problems or deficiencies to be overcome or satisfied. The final section of this Technical Memorandum also summarizes in more detail the plans and anticipated schedule for this development effort.

## BACKGROUND

Recent work at the Civil Engineering Laboratory on nearshore trafficability identified advances in two areas which impact deep ocean trafficability. These advances include developments underway in the private sector to develop and utilize vehicles using active running gear systems on the seafloor, and major research efforts by the Army Engineers directed at solving mobility problems on extremely weak and cohesive soil in terrestrial dredge spoil reservoir areas. The successes in these two areas suggested that important advancements applicable to the deep ocean trafficability problem had taken place since the Navy's last major evaluation of this field in 1970 (see Wiendieck, 1970). As a result, it appeared that the potential for a successful development effort on an active running gear system for use in the deep ocean was now sufficiently

high for undertaking such an effort.

The Deep Ocean Technology (DOT) program undertook the sponsorship of this effort which is directed at the development and demonstration of the technology of deep ocean trafficability and also deep ocean work enhancement of existing seafloor work vehicles by the addition of a running gear module. This modular approach was selected because of its cost effectiveness when compared to the cost of developing an entirely new vehicle utilizing an active running gear system. The approach is to use an operational seafloor vehicle as a host vehicle during the test and evaluation of the running gear module. After successful testing and demonstration of the module hardware, it will become a dedicated accessory to the host vehicle and available for use on jobs requiring the position maintenance or force development or reaction afforded by use of an active running gear system.

A surprisingly large number of bottom-crawling vehicles have been designed, fabricated and used on the seafloor, a few by the Navy, but the vast majority by private companies. Many vehicles in the latter category serve functions analogous to those required by the Navy. The vast majority of these vehicles are designed for operation in the near-shore environment at shallower water depths and generally on more competent soils. While the trafficability-related performance data on these vehicles are very limited, the existence of these various vehicles, their design parameters, and existing general information on their general performance are all of value to the efforts summarized in this report. A detailed summary of these existing vehicles along with their characteristics and additional information on their performance is summarized in the section which follows.

The bottom-crawling vehicles which have been developed by the Navy have been used primarily for research or technology advancement. In a few cases the vehicles with their running gear were designed to support a specific requirement, usually in the form of a job or project to be accomplished. There is no known Navy requirement specifically calling for a running gear module for a deep ocean vehicle. Rather, there are numerous Navy requirements for specific systems, facilities or operational capabilities which, in turn, require improved seafloor work and salvage capabilities.

In many cases these capabilities are currently severely restricted. In those cases and others, they could be enhanced by the addition of a running gear module. Examples of requirements for work capabilities and of vehicle concepts developed in response to such requirements are summarized in a subsequent section.

The concept outlined in this report is that of a running gear module which would be designed as a dedicated accessory to a specific host vehicle. A number of potential host vehicles, both within the Navy and in the commercial arena, are summarized in a subsequent section. In concept, the running gear module could be designed for either a manned or unmanned vehicle. However, because of the high cost and increased time required for testing, verifying, documenting and certifying a system to be used on a manned vehicle, it is planned that this development

effort will be directed toward a running gear module designed for an unmanned vehicle. The technology, however, is useable directly on a manned vehicle.

Existing Bottom-Crawling Vehicles

A large number of bottom-crawling vehicles have been designed and built for use on the seafloor. These vehicles have been built for a variety of missions, including site survey, inspection, pipeline or cable burial, dredging or material removal, and for support of a variety of research projects. While the plans for, and existence of, a number of these vehicles are well documented especially in the trade literature, information on the mobility-related performance of most of these vehicles is extremely limited and in most cases, non-existent. The results of a thorough search of the literature concerning such vehicles is summarized in Table 1 with additional information about each of the vehicles summarized in the paragraphs below.

Anderson Undersea Crawler. This vehicle was built by the Anderson Undersea Company in San Diego some time ago as an experimental model designed for carrying small instrument packages, particularly for inspection work. It was quite small, 40-inches long by 44 inches wide and only 15 inches high. It was used in San Diego Bay on at least one project where it reportedly performed quite satisfactorily on extremely weak mud. The track appears to have been custom built and was made up of rubber or plastic track shoes connected by two parallel continuous type flexible drive-chains.

Aquatech Cable Plow. This vehicle has a passive running gear system. Forward motion is achieved by being towed by surface ships. The vehicle uses a stinger with water jets on it to bury a cable to a maximum soil depth of six feet. The vehicle was used, apparently successfully, on at least one job on a lake bottom. Aquatech is located in Lebonnen, Connecticut.

Atlantic Marine Dredge Sled. This vehicle appears from photographs to be a skid-mounted vehicle of the order of 10 feet in length. It was apparently designed for clearing sediment from a trench which had been previously dug for burial of cables and which had since been backfilled by natural processes. The vehicle was apparently used successfully on at least one job in the New Brunswick, Prince Edward Island area. The vehicle was designed and used by the Atlantic Marine and Diving Company, Ltd, of Fredrickton, New Brunswick, Canada.

Atlas Copco Roc-601M. This vehicle is a modified version of the Atlas Copco's standard 601 model track rock drill for drilling blast holes in rock. The vehicle was nominally 10 feet long by 7 feet wide and was used on at least one job on the seafloor in the Scandinavian area. The vehicle belongs to Atlas Copco in Sweden.

Bell Sea Plows. Bell Laboratory of the American Telephone and Telegraph Company has over the last decade or so evolved a series of vehicles, each one apparently utilizing many of the components of its predecessor. Each has used skids described as toboggan skids and has a plowshare type burial device for burying the cable approximately 2 feet deep. Sea plows I and II were both 24 feet long by 11 feet wide. The two skids in the front were 6 feet long by 2½ feet wide, and the two in the rear were 2 feet shorter. Sea Plow III used a larger single skid in the front and its overall length was approximately 30 feet. Sea Plow IV appears to be similar or slightly larger. The forces required to tow these vehicles are quite large. In the case of Sea Plow III the cable tensions in the towing cable ranged from 7,000 to 14,000 pounds for towing the vehicle with the plowshare up. With the plowshare down, forces varied from 11,000 to 37,000 pounds. The Bell Survey Sled was apparently used as a survey vehicle for work with Sea Plow I. It was similar to the Sea Plow I but was smaller and apparently lighter in weight.

Cammell Laird Vehicle. This vehicle was designed as a diver lock-out vehicle to support diver work on the seafloor. It had four wheels 8 feet in diameter by approximately 3 feet wide. The vehicle itself was 48 feet long by 19 feet wide. The vehicle never became operational and parts have been salvaged for use on other vehicles. The vehicle was designed and fabricated by Cammell Laird in England.

Cal Eastern Seacat. This vehicle utilized a converted Caterpillar D-7 track system to support what appears to be a manned chamber similar to a submersible. The vehicle was used for inspection work and for light work with several manipulators. The vehicle belonged to the California Eastern Engineering Company.

CEL Cable Plow. This vehicle is still in the design stages; however, tests of reduced scale components such as the water lubricated skids have already been completed. This piece of equipment is being developed by the Navy's Civil Engineering Laboratory in Port Hueneme, California.

CEL Equipment Test Chassis. This vehicle consisted of a single track and was designed for trafficability research on the seafloor. The track was of the continuous belt type with aluminum grousers approximately one-inch high spaced about 8 inches apart. The track footprint of bearing area was 52 inches long by 14 inches wide. The track system would be classed as a rigid track in the sense that the bottom side of the track was supported by a water lubricated skid pan rather than by compliant road wheels as is common on higher speed tracked vehicles. A fairly extensive number of trafficability performance data were gathered using this track in underwater environments including one site in Chesapeake Bay and four sites off the California coast.

CEL Track Drill. This vehicle was a slightly modified standard Navy issue Worthington Model 1290D track drill. It was used at several sites in the Atlantic and Pacific, in areas of very rugged rock. The only problems encountered from a trafficability standpoint involved the extremely rugged rock surfaces and an inability of the vehicle to negotiatc some of these extremely large obstacles.

Comex Cable Plow. This track vehicle was initially built to accommodate a manned submersible which sat on top of it and controlled its operations. It has more recently been reconfigured for operation by divers. The vehicle uses a Poclain track unit modified for use under water. The tracked vehicle is approximately 19 feet long by 11 feet wide. The tracks were initially approximately 2.6 feet wide and were later changed to use what is commonly called a delta track shoe. These track shoes were approximately 4 feet wide. This vehicle was successfully used for a number of cable burial jobs. While the trafficability performance was generally satisfactory, comments of the operators indicated that traction in very soft soil was occasionally insufficient to pull the plow. The plow utilized a number of lower pressure water jets. It is understood that the vehicle is being modified for cutting small trenches in weaker rock for cable burial on a new project.

CNEXO Test Module. This was a reduced scale model of the running gear portion of a nodule mining vehicle. The two skids measured approximately 9 feet long by 9 inches wide. The vehicle was tested in a soil bin using bentonite clay and was also apparently tested on the seafloor on a "Red Clay." The forces required to tow the vehicle on the Red Clay were of the same order of magnitude as the vehicle weight. The vehicle belongs to CNEXO in Brest, France.

CrawlCutter. This vehicle was built utilizing a Caterpillar D-9 track system. The vehicle was approximately 26 feet long by 13 feet wide,and the individual tracks were 14 feet long. The vehicle was used extensively in the area around Florida and apparently functioned quite satisfactorily from a trafficability standpoint with over nine months of underwater time logged. The vehicle is known to have encountered some rather high obstacles during its work underwater. One of the obstacles was a coral bank at least 5 feet tall. Because of the geometric configuration of the vehicle, it was not capable of surmounting this obstacle. However, because of its mechanical strength and configuration, it was able to in effect eat its way through the bank and to tear it down. No trafficability problems on sand have been reported. The vehicle was built by a subsidiary of the Ocean Science and Engineering Company of Long Beach. The subsidiary's name was Ocean Dredging, Inc., of Fort Pierce, Florida. The vehicle has reportedly been recently sold to a Japanese interest.

Gopher Mark II. This vehicle measures approximately 20 feet long by 8 feet wide and is towed by a surface craft. Tow forces have reached as high as 20,000 pounds while plowing a trench 4½ feet deep. The vehicle belongs to Undersea Systems, Inc., of Alexandria, Virginia.

Harmstorf Vehicles. Harmstorf of Holland, with offices in other countries including the U.S., has been involved with several vehicles designed for cable and pipeline burial. Like the Bell Seaplows, these several Harmstorf vehicles are likely outgrowths or improved versions of earlier vehicles. All are pulled from a surface ship or from a winch system anchored on a beach. The Harmstorf crawler did have a hydraulically-operated track system, but this was designed primarily to allow the vehicle to negotiate rugged terrain with the real drawbar for propelling the vehicle obtained from a surface ship. Several of the vehicles used a stinger with water jets to embed the cable or pipeline being buried; the depth of burial in several cases was as large as 6 to 8 feet.

Hitachi Vehicles. Hitachi in Japan, in several instances in conjunction with the Japan Development and Construction Company Ltd., known as the Jadecco, has built a number of vehicles which function as bulldozers or as survey vehicles resembling bulldozers. Most have been hydraulically powered from the surface and several have used air-filled variable buoyancy tanks for controlling bearing pressure of the tracks. The vehicles have varied in length from a maximum of 23 feet to a minimum of 17 feet with widths varying from 17 feet down to 10 feet. The vehicles have apparently performed satisfactorily from a trafficability standpoint on materials which appear to be granular in nature. One bulldozer, the Underwater Bulldozer No. 2, is reported to have developed drawbar pulls as large as 22,000 pounds. The survey vehicle carries an "underwater surveillance system" which is part of the "Seabed Civil Engineering Working System," which includes a series of coring devices.

Jet Barge III and IV. Both of these vehicles are apparently very large skid-mounted structures designed for digging trenches in which large pipe lines will be buried. The vehicles have apparently been used successfully in the North Sea area.

Jetco Trencher. This vehicle used a rock wheel to cut an 8-foot deep trench in coral and weaker materials. The vehicle was successfully used at least once underwater in a river crossing in Holland. The vehicle is owned by Jetco in Dallas, Texas.

Kennecott Nodule Mining Vehicle. This vehicle was the fifth in a series designed and fabricated by Kennecott Exploration, Inc., in the process of refining the design of an eventually operational nodule collection vehicle. This vehicle was towed by a surface ship

at great water depths. The vehicle experienced a stick/slip periodic motion on the seafloor, presumably the result of the cohesion of the deep ocean clays and partially the result of the elasticity in the towing system. The vehicle underwent approximately 50 days of operational testing in the deep ocean and apparently experienced no trafficability related problems other than the occasional stick/slip motion mentioned above and an occasional problem with large obstacles. The areas in which such a vehicle is typically used apparently contain a number of large obstacles, and as a result, this vehicle was designed for impact with very large obstacles, and as part of this design, had a self-righting capability for recovery after impacting such an obstacle. These capabilities were apparently needed and did function as intended to a large extent, although in one case the tow cable was damaged due to numerous roll overs of the vehicle.

Komatsu Bulldozers. Komatsu of Japan has built a large series of bulldozer/rippers for use in the surfzone and nearshore regions. These have been both electrically and hydraulically powered. Seven of these vehicles are listed in Table 1. It is not possible to tell from the literature whether some are simply modifications of earlier vehicles. However, the literature does indicate that at least eleven different vehicles have been fabricated by Komatsu. The vehicles are large with lengths up to 27 feet and widths to 13 feet. The vehicles have apparently been used quite successfully on a number of jobs in what appear to be protected waters where large volumes of sand and gravel have been moved. Details of the actual trafficability performance of the various vehicles are not available; however, it is known that drawbars as large as 95,000 pounds have been realized. These various bulldozers have operating speeds up to 5 miles-per-hour and reportedly can operate on grades as steep as 30 degrees.

Komatsu Walking Machine. Komatsu has also developed an underwater robot which is computer controlled from a surface ship through an electrical umbilical. The vehicle/robot can travel at speeds up to 500 meters-per-hour and reportedly can operate in tidal currents up to 6 knots. The vehicle is roughly 23 feet long by 15 feet wide and can reportedly walk over extremely rugged terrain.

Kvaerner Pipeline Dredge. This very large vehicle, approximately 30 feet cubed, rides on the pipeline using what appear to be at least 12 rollers or wheels which are powered. Tests were successfully completed with a reduced scale prototype several years ago. The vehicle belongs to Kvaerner Bruge A/S in Oslo.

Naucrates. This vehicle can be operated manned or unmanned and utilizes a slack hanging chain. The running gear functions in the following manner. The vehicle is positively buoyant until the hanging chain is attached. This hanging chain is like a slack track system, and the vehicle settles to the bottom until sufficient track chain is

on the seafloor to balance out the buoyancy of the vehicle. As this hanging chain is run forward or backward, the vehicle moves along with it. The ground pressure of this chain on the seafloor is extremely small, and this form of a running gear can accommodate rugged terrain. However, this type of running gear is not capable of developing any significant drawbar force or of resisting significant forces such as from current drag.

Nippon Telephone and Telegraph Cable Plow. This is an early cable plow designed for use in very shallow water. It utilized water jets to bury the cable. A more recent plow, listed below under Sumitomo, Mark III Cable Burier, is presumably the most recent addition to the family.

Norges Vassdrags Cable Burier. This vehicle was designed with four unpowered wheels for maintaining mobility on sand and small rocks while being towed by a surface ship. The vehicle apparently experienced no mobility problems while burying over 25 kilometers of a large electrical power cable to a soil depth of 1 meter on the Danish end of a cable linking Norway and Denmark.

Oceanic Mole and Seamole. Two pipeline burial vehicles, the latter is likely an improved version of the former, have been used by Oceanics, Inc., of Houston, Texas. The vehicles carry a pair of counter-rotating cutter wheels to bury the pipe and have apparently functioned satisfactorily in clayey materials.

PMTC Trencher. This vehicle is a Vermeer T600C trencher modified for underwater use, originally by the Civil Engineering Laboratory and subsequently by the Pacific Missile Test Center. The vehicle was first used at Midway Island where it functioned properly on the sand for which it was intended. However, it had difficulty with very rugged terrain on a coral reef, an environment for which the track system was not suitable. The vehicle was subsequently modified and used in Kauai, Hawaii. At this site the vehicle performed marginally satisfactorily from a trafficability standpoint in that it functioned properly on sand except in the surfzone area where at extremely low speeds and high drawbar pull, the track tended to bury itself and become immobilized. At this site the vehicle was also used in the surfzone on some rougher terrain and in rough surf where the track system again had difficulties eventually resulting in a serious mechanical breakdown.

Ponga Cutter Head Dredge. This is a large sled-like vehicle approximately 40 feet long by 26 feet wide which is towed by a surface ship. The vehicle has four inclined axis milling drums which operate like cutter head dredges for burial of pipes as large as 60 inches in diameter. These dredges can cut trenches as deep as 8 feet in fairly stiff clay. No data on trafficability performance were found available.

RJBA Plow. This vehicle is basically an extremely large plow with two wheels, which is towed by a surface ship. The plow vehicle is 40 feet long, and the two wheels are approximately 10 feet in diameter.

There are two cutting discs 8 feet in diameter in front of the plowshare. Tow forces at the towing vessel averaged 80 tons and peak requirements or peak forces were as large as 120 to 150 tons. The vehicle apparently performed satisfactorily from a trafficability standpoint. The vehicle was designed by, and apparently the property of, R. J. Brown and Associates in the Hague, Netherlands.

RUM I and II. RUM I was built originally in the 1957-1960 timeframe to work from the beach out. The undercarriage and track system was a surplus Marine Corps ONTOS Weapons Carrier, and the vehicle in its original configuration carried and paid out its power-control umbilical cable from a reel mounted on the chassis, see Figure 1. RUM I was tested in San Diego Bay in soft sediments where in at least one test it bellied out and became immobilized according to Taylor, 1962.

In the late 1960's the RUM was reconfigured as RUM II with general characteristics as summarized in Table 2. Using the ORB surface support platform and its constant tension winch system for handling the RUM II, it was possible to vary the RUM's ground pressure from 0 to 3.0 psi. The vehicle has been used at a number of sites, but more detailed observations or data on track performance are available from only a few including San Diego Bay, San Diego Trough, San Clemente Basin, and the La Jolla Canyon area. These sites are in water depths to 6,000 feet. The one set of track performance data for which relevant geotechnical data are also available is summarized in Table 3. Data from Anderson, et al (1972) indicates the following: a) the remolded shear strength at the soil depth controlling trafficability (the upper 6 to 12 inches) is 0.09 psi; b) the sensitivity is 3.3; and c) the soil is a highly plastic clayey silt with a plasticity index of 33 to 44. The data in Table 3 suggest that bearing pressures above 0.75 psi are too large for this location. The drawbar coefficient (drawbar force divided by track bearing area) is relatively constant at lower track pressures with a maximum of 0.17 which occurs at a track bearing pressure of 0.75 psi. This drawbar coefficient corresponds to approximately one-half the undisturbed shear strength of the soil and slightly less than twice the soil's remolded shear strength. Figure 2 illustrates similar drawbar coefficient data as a function of track pressure for other tests with RUM II.

The general operating experience with RUM II is discussed in several references - Anderson, et al (1970), Anderson, et al (1972), Anderson and Gibson (1970), Anderson and Gibson (1972), and Gibson and Anderson (1974). A number of important observations and conclusions have been made by the RUM investigators. These include the following:

a) in weaker soils as higher ground/track pressures are applied the realizable drawbar force decreases and sinkage increases until the vehicle "bottoms out" and becomes totally immobilized;

Sieverts Cable Plow. This vehicle is basically a towed sled designed for burying electrical power cable one foot deep. The plow operated successfully over a distance of 13½ miles. The plow was fabricated and used by Sieverts Kabelverk, in Sweden.

Subsea Oil Services Vehicles. Subsea Oil Services, Milan, Italy, has developed a series of underwater vehicles to support pipeline burial operations. Several of these ride on the pipeline rather than on the adjacent soil. They have also developed a track drill for drilling and breaking up rock in the path of the pipeline burial work.

Sumitomo Cable Burier Mark III. This vehicle is a cable plow similar to those developed by Bell. This vehicle is towed by a large ship and has apparently performed satisfactorily over cable runs totalling more than 100 kilometers. The vehicle was developed by Sumitomo Electric in Yokohama, Japan, in conjunction with Nippon Electric Company and Nippon Telephone and Telegraph Corporation.

Sumitomo Trenchers. Sumitomo Shipbuilding has been involved with the development of what appears to be two separate trenchers which utilized a cutter head dredge for removing material. At least one of them was successfully used in Sagami Bay. No other information is available concerning their trafficability performance.

Tango Trencher. This is a very large pipeline burial vehicle which apparently uses some form of track. The vehicle is 70 feet long by 27 feet wide and has a large, approximately 6 feet in diameter, cutter head. No other data are available except that typical maximum speeds while cutting are 160 feet-per-hour and 360 feet-per-hour for clay and sand, respectively.

Technomare Burial Vehicles. Technomare in Italy has built and tested one prototype vehicle and is in the process of building a second designated the TM 402. These very large vehicles utilize two construction type tracks. The first prototype vehicle, the TM 102, apparently operated satisfactorily during tests of its running gear system on clay and rocky soils. The new vehicle is scheduled for tests in the Mediterranean in 1979.

Tramp Prototype. Winn Technology Ltd., in Ireland, is developing a family of inspection type vehicles which utilize six rubber tired wheels and an articulated frame to accommodate large obstacles. One reduced-scale prototype has been tested offshore and with reportedly good success. A larger 16,000-pound prototype has apparently been fabricated, and a larger version is planned.

Vickers Seacat. This vehicle is designed for cable burial using a water jetting system. It utilizes eight high flotation type tires and has apparently performed quite satisfactorily from a trafficability standpoint. Vickers Oceanics in Edinburgh, Scotland, is currently

b) as track pressures are increased, but well before excessive sinkage occurs, difficulty with steering is experienced;

c) the particular track used on the RUM "fills up" with soil easily, preventing grouser penetration (there are conflicting views on the effect of this, but it appears not to degrade performance significantly; the data presented in Table 3 and Figure 2 were obtained with "filled tracks" according to Gibson, 1978);

d) use of the track at some sites stirs up a well defined turbidity cloud which is described as being 2 to 6 inches thick and spreading at speeds of the order of one-half foot-per-second, independent of any bottom currents;

e) the depression left by the track is usually filled in by this dense turbidity cloud;

f) soil was also "thrown off" the track, but this generally did not have a major effect upon visibility since the RUM operators always work up current;

g) at typical deeper ocean sites it is usually necessary to operate RUM at ground/track pressures of less than 1 psi, lower than 0.5 psi in several cases; and

h) drawbar forces of up to 1,000 pounds (0.25 psi) are achievable at many sites.

It should be noted that while the RUM has demonstrated significant performance characteristics in several situations, it is by no means a track design optimized for the deep ocean environment. Thus, the use of a different track unit on RUM or on any other vehicle might be expected to provide improved performance characteristics if properly designed.

Saclay Test Unit. This is a small-scale working model of a vehicle to be used for nodule mining. This scale model uses an Archimedean screw which is one foot in diameter. Tests in a marshy area in the south of France produced drawbar pulls of 200 pounds but require a 1 kilowatt energy input. The vehicle is being developed by the Centre du'Etudes Nucleaires in Saclay, France.

Seabug 1. This vehicle uses four water-filled tires. The front two tires are steerable by a swing axle. Dual tires or extra wide tires can also be used. The vehicle has been tested on sand and in rocky areas and performed satisfactorily. The vehicle is operated by UDI in Aberdeen, Scotland.

developing a second vehicle called the Seadog which may be a modification of the first, for trenching in harder materials such as weaker rock.

Summary. Table 1 and the paragraphs above summarize available information on over 60 past, present and three near-term future seafloor work vehicles. More than a third of these vehicles use a passive running gear system such as skids and are towed by surface ships; thus, they are not of primary interest to this development effort.

Of the 40 vehicles which use active running gear systems, 38 have been built and presumably operated; about a quarter of these are thought to be modified versions of earlier vehicles. Half of these 38 vehicles are thought to still exist today. The majority of these have been designed and built for one or two specific jobs. Only one is known to have been used on more than four jobs. Thus, while a large number of vehicles have been built, very little experience operating the vehicles on the seafloor exists. Of the vehicles using active running gear designed for cohesive soils, few were developed for research purposes and only one for research on seafloor trafficability--the CEL Equipment Chassis Test Track (ECTT). Unfortunately, the ECTT and RUM are the only vehicles with which quantitative measurements of mobility on seafloor soils have been obtained and are available. For the few other vehicles for which such measurements are thought to have been taken, such information is considered quite proprietary by the vehicle operators and not available to others. For the vast majority of these vehicles with active running gear systems, no measurements have ever been taken and at best, non-expert visual observations of general performance are available. In most cases there is either a total lack of performance information or enthusiastic but undocumented and very generalized reports of totally satisfactory performance. Even for the research vehicles, the author knows of only four instances where vehicle performance and relevant soil properties were both measured at seafloor sites. Thus, while a fairly large number of vehicles have been built and many of these operated on the seafloor at least once or twice, the data available on seafloor trafficability and running gear performance are extremely limited. Nevertheless, the fact that vehicles have been designed and apparently used successfully is valuable information and contributes to the technology in that the vehicle's design characteristics and reported successes and problems provide generalized data points on seafloor mobility, and running gear performance.

The sites and environmental conditions for which these vehicles have been designed and which they have encountered are typically less severe (stronger and more competent soils) than those expected for the deep ocean running gear module being considered here. In addition, the mission scenarios for these vehicles (size of vehicle and its required performance in terms of drawbar force development, reaction to forces, submerged bearing pressure, etc.) are in general quite different from those for the Running Gear Module. Thus, while the

existence of these vehicles, their design characteristics, and their seafloor mobility related performance levels are of significant value to this study, they do not provide sufficient information in a number of technical areas to allow satisfactory design at this time of a running gear module for the deep ocean environment and the work mission scenarios envisioned.

It was intially hoped that one of these vehicles could be used to generate the mobility data required to satisfy the technical deficiencies remaining; however, of the 19 or so vehicles which could be considered, only three have running gear configurations appropriate to this study. Of these three, one belongs to a foreign group which has been approached concerning our mutual interests but is not interested. A second vehicle is on an inactive status and would require extensive work (hundred-of-thousands of dollars) to make it operational. The third vehicle no longer exists. Several larger vehicles could, from a technical standpoint, be used; however, the costs of required modifications to obtain the needed data and the costs of their operation were judged to be well beyond the means of this development effort.

Navy Needs

As mentioned earlier, there is no known Navy requirement which specifically calls for a running gear system for use in the deep ocean. However, there are numerous Navy requirements and needs for improved work capability on the deep ocean seafloor. The objective of the Deep Ocean Technology (DOT) program is technology development in support of the various Navy requirements. The objective of this DOT project is the development of a running gear technology to support work capability enhancement. This enhanced work capability for the deep ocean will be in terms of construction and salvage types of work.

The Navy has a number of needs for running gear for the deep ocean seafloor, as demonstrated by the existence of a number of on-going development projects and procurements, which are listed below.

<u>Deep Ocean Cable Burial System</u>. The Naval Facilities Engineering Command is funding the development of a deep ocean cable burial system at the Civil Engineering Laboratory. The concept as currently being developed utilizes a passive skid system as the running gear and thrusters to develop the required force for forward motion and cable burial. An active/powered running gear system would be preferable from many standpoints (including energy consumption); however, the state-of-the-art of active running gear technology was judged to be too underdeveloped and thus too unreliable for use at the time that the concept was formulated for this eventually operational system.

<u>Navy Range Work</u>. The majority of this work involves the recovery of test weapons which sink to the seafloor and in some areas embed themselves in the seafloor. An obvious example is the work at the Navy Torpedo Station at Washington, which utilizes two SORD vehicles and a CURV II vehicle to recover weapons from on or in the seafloor at

their two underwater ranges. Keyport is in the process of developing or procuring a new vehicle which will hopefully combine the capabilities of their two existing vehicle systems. The existing SORD vehicles are large and require the use of a heavy three-point mooring system for their deployment. This is required in part to support the large weight of the vehicle and the forces from its jetting system used for recovering buried weapons. Their existing CURV II vehicle is easily deployed, but because it is free-swimming and does not have the capability to provide the needed reaction for a jetting system, it is not capable of recovering weapons systems that are buried to any soil depth. The new vehicle system as envisioned by Keyport, will hopefully embody the versatility and easy handling characteristics of the CURV II along with a jetting capability approaching that in the SORD vehicles. Use of an active running gear system is one logical approach to developing this capability.

Improved Salvage Cability. The CURV III, the RUWS, and several Navy submersibles are used for salvage jobs in the open ocean. The Work Systems Package (WSP) was developed as an accessory for use on several of these vehicles to provide an expanded tool suite to enhance work capability. The WSP utilizes two grabbers together with a manipulator. The grabbers are utilized to hold the Work Systems Package fixed relative to the object being worked on with the manipulator. In this way, the reaction force required for any tools being used by the manipulator is transmitted directly back to the object through the grabbers. This approach works satisfactorily in many cases; however, there are exceptions. In one instance because of a cross-current, the drag forces on the host vehicle were sufficiently large to bend and damage one of the grabbers. In another instance the object being worked on did not have structural members of sufficient strength to which the grabbers could attach for a good reaction. They ended up tearing the structure apart to some extent and not being able to perform the work originally planned. Experience with the CURV vehicle has illustrated the difficulty of doing precise work in a cross-current. An example was the placement of the Foundation Monitor System on the SEACON I foundation in the Santa Barbara Channel. In that case, a slight cross-current on the order of 0.2 knots, made it impossible to place the instrumentation package in a cradle designed to accept the package once the position was within one foot of central location. In additional experiences with the CURV vehicle at the SEACON I site and also at the 1200-foot-site in the Santa Barbara Channel, work had to be slowed to an extremely slow rate because of limited visibility and the proximity of several objects in which the vehicle could potentially become entangled. As a result, the physical approach to any one object using sonar was done in small hops with a two or three minite pause between hops so that sonar fixes could again be obtained in planning for the next small movement towards the object of interest. A running gear system which maintains constant contact with the seafloor and thus known position would allow for a more continuous operation in situations such as this.

Deep Ocean Recovery System. Preliminary development of a new Deep Ocean Recovery System (DORS) is currently underway under the Extended Depth Salvage Capability program. The Work Vehicle portion of this system must be capable of reacting to the large current drag (as high as 4 knots for some shallower water scenarios) on both the vehicle and the large diameter power umbilical cable to the vehicle. The vehicle concept is currently 8 by 8 by 25 feet, has a mass of 15 tons, and is neutrally buoyant. An active running gear system with a drawbar of about 5,000 pounds is one approach to accomplishing this reaction while on the seafloor at a minimum cost in terms of the available energy budget. The vehicle is to have about 150 horsepower, 50 in vertically directed thrusters.

Nearshore Trenching. There have been several recent instances where the Navy had an interest in trenching in weak cohesive sediments in the nearshore environment--an environment similar to that of the deep ocean and one requiring the same type of running gear technology. These trenching requirements were for cable burial or more often for the burial of sewer outfall lines. In both cases a burial vehicle utilizing an active running gear system would require much less surface support than would a vehicle using a passive running gear system and dependent upon the surface tug for thrust development and positioning.

## Potential Host Vehicles

The modularized running gear approach is applicable to both manned and unmanned vehicles, and in fact, the technology being developed in this effort is meant to be applicable to both types of vehicles. However, for the sake of economic and timely completion, it has been decided that the first running gear module will be designed, built, and tested for an unmanned vehicle.

Table 4 lists the known, active unmanned vehicles potentially available on the commerical market as host vehicles for a running gear module. Table 5 lists potential Navy host vehicles including both unmanned and manned vehicles. The latter category are listed simply for future reference. It was initially assumed that a Navy vehicle would be used as the host vehicle. However, most of these vehicles are in fairly continuous use on high priority projects or are required to be on a stand-by status for potential emergency requirements. Thus, they may not be available for work on an R&D effort such as this one. For this reason the use of a commercial host vehicle is considered a reasonable possibility, particularly, if the owners are interested in a cooperative effort to develop the running gear hardware which would be dedicated to their vehicles.

Major questions to be addressed in selecting a host vehicle include the availability of the vehicle, the interest on the part of vehicle owners/operators in a running gear module, and physical compatibility of the potential host vehicle with the requirements of the running gear module. Only the latter question can be addressed here. Tables 4 and 5 include the information available in the literature that pertains to physical, mechanical, electrical, and control configurations

as they affect the compatibility of the host vehicle to the proposed running gear module. Payload and payload capacity indicate the amount of weight in air that can be added to the vehicle without causing significant handling problems. In many cases it is reasonable to assume that additional weight could easily be handled as long as balancing buoyancy were also added--likely in the form of syntactic foam. Available vertical thrust in terms of horsepower or pounds is listed as an indication of the effective bearing pressure that could be obtained using the vertical thruster alone. A typical relationship between horsepower and thrust for recently designed, highly efficient thrusters in the 10 horsepower range, suggest that 30 - 50 pounds of thrust per horsepower can be developed. Work capability and a description of manipulators is included so that an assessment of potential work enhancement for the various potential host vehicles can be made. The available power on each of the vehicles is summarized in terms of the total horsepower apparently available at the vehicle which could conceivably be used for powering a running gear if other powered systems are not in use. An effort was made to determine the number of extra control channels available on some of these vehicles; however, specific information was not found to be generally available. It is assumed that for many of these vehicles, particularly the more recent ones that are oriented towards amodular approach for tool packages, that a number of control channels are available which would be sufficient for operating an active running gear system.

In addition to the vehicles listed in Tables 4 and 5, other potential host vehicles do exist. One of these is the RUM vehicle at Scripps. This vehicle is a bottom crawler which conceivably could be modified to accept a new running gear system. However, information provided by personnel at Scripps Marine Physical Laboratory suggests that the cost of reactivating RUM would be in excess of $200,000 plus the cost of any modifications for new running gear. There is also the possibility of developing the planned running gear module in conjunction with other new vehicle development efforts. An example is the very preliminary work at Scripps on a deep ocean survey vehicle which may include a bottom running gear system. Other possibilities include the planned overhaul and modernization of the CURV III, the new vehicle planned by NTS Keyport, and the DOT funded Deep Ocean Recovery System vehicle development effort. Selection of the host vehicle must take into consideration the questions outlined above and the status of the various vehicles, or their development efforts, at the time the decision is made--see the final section of this report for an approximate schedule of events.

## MOBILITY ASSESSMENT

### Deep Ocean Environmental Conditions

The environmental parameters of primary importance include soil type (fine-grained or coarse-grained), relevant strength parameters

(something approaching a remolded strength for fine-grained soils and a measurement approaching a cone gradient for coarser grained soils), local slope angle, and a description of obstacles which might have to be surmounted (described in terms of their scale and geometry). In addition to the preceding parameters which determine vehicle mobility, bottom current velocity is important in determining lateral forces on the vehicle and in analyzing its stability relative to lateral sliding or overturning in the case of extreme vehicle positions.

The geographic distribution of general sediment types in the deep ocean is summarized in Figure 3, and the frequency of occurrence of the various types are listed in Table 6. Areal variability, which controls capabilities to generalize typical conditions, is a major problem in shallower water (continental shelves and adjacent areas) and in the vicinity of major topographic features such as hills and seamounts. Evaluations of controlling parameters in such areas should be on a case by case basis. Local slopes and obstacle heights to be negotiated in such areas are often excessive, and thus the areas prove to be non-trafficable from a practical standpoint. Such non-trafficable areas likely make up much less than 5% of the total seafloor area. From an operational interest standpoint they may, however, constitute more than 5% of the areas of interest.

For typical deeper ocean areas the following ranges of properties are likely applicable to the upper foot or so of sediment (developed by H. Lee and published in Rockwell, 1976):

| | |
|---|---|
| Shear strength in cohesive soils | 0.18 to 2.2 psi |
| Bulk/total unit weight | 78 to 116 pcf |
| Angle of internal friction in granular soils | 30 to 42 degrees |

The first two values apply with more confidence to pelagic clays, often termed red or brown clays. An analysis of another large set of core data reported by Richards and Parks (1977) covers the north-central Pacific where pelagic and siliceous pelagic clays predominate. These data suggest that a typical remolded strength in the upper foot is 0.17 psi. However, this is an average for data which were widely scattered.

Properties for the various deep ocean oozes are not well documented in the literature. A large study by Lee (1978) of a band of "more plastic" calcareous ooze across the equatorial Pacific suggested a minimum (exceeded by at least 90% of all measurements) remolded strength at shallow soil depths of 0.09 psi with sensitivities of about 5. It is generally anticipated that other oozes would have similar properties. Oozes with very little or no clay filler (not a typical condition) will likely have properties fitting into the above ranges, but may exhibit behavior patterns which are somewhat unusual by terrestrial standards and which may cause difficulty in assessing likely trafficability performance. The somewhat unusual behavior is primarily related to the very high void ratios of these "clean" oozes and the potential for densification and significant strength loss under

loads that are vibratory or cyclic in nature.

Based on the soil strengths indicated above together with the assumption of typical sensitivities in the near surface sediments of 2.5 to 3.0, the following design values are assumed for fine-grained plastic sediments:

| | |
|---|---|
| Undisturbed strength | 0.3 psi |
| Cone index | 3 |
| Remolded shear strength | 0.1 psi |
| Sensitivity | 3 |

Data from most studies utilizing well-designed corers or box corers in deep ocean environments indicate that the soil strengths are relatively constant (gradients less than 30% in the upper foot) over the soil depths which control trafficability behavior--0 to 12 inches for this type of soft soil environment and the small to moderate scale of the equipment involved. Numerous investigators have noticed a layer of very loose soil/"fluff" at many locations. When present, this layer is usually less than 3-inches thick and often of the order of only one-quarter inch thick (just enough material to destroy visibility when a thruster is activated). This layer is ignored in the analysis of trafficability since it is likely simply displaced by the track or running gear system and pushed out of the way. This assumption appears quite reasonable based on experience and direct observations with the RUM vehicle.

The performance of any running gear system is influenced by the angle of the slope on which it is operating. The effect of this slope angle is larger in weak or loose soils. The effect is in terms of the following: (a) the additional tractive effort which must go into moving a vehicle upslope, thus leaving less tractive effort available for development of drawbar pull for external use; (b) the reduction in bearing pressure acting normal to the soil surface (due to the inclination, the component of the negative buoyancy which acts normal to the soil surface is reduced)which will typically result in reduced traction; and (c) the increased potential for slope instability due to the "weight"/negative buoyancy of the vehicle acting on the slope.

Slopes on the seafloor are, on average, quite gentle. However, they vary by geographic location and can be quite significant.

Continental Shelf. The average gradient is 7 minutes but 5-degree local slopes are common.

Continental Slope. The average gradient worldwide is 4 degrees. It is about 50% greater for slopes off what are termed fault-coasts such as California and major portions of the western coasts of the north and south American continents. Local slopes are much steeper. Slopes as steep as 25 degrees occur in some areas.

Deep Ocean Seafloor. The deep ocean seafloor on average has a gradient of less than 3 minutes. However, local features such as rises and hills have larger slope angles.

Trenches and Seamounts. These large features have much steeper slopes. Average maximum slope angles typically range between 4 and 16 degrees with extreme values to 25 degrees.

Summary of Slopes. The vast majority of the seafloor (probably greater than 98% of the total area) has a slope angle less than 5 degrees. The extreme values (to 25 degrees) listed above occur frequently enough to be statistically significant. Steeper slopes (to 90 degrees and even steeper--overhanging) do occur. And while these are spectacular, well documented, and well publicized, they are not common or significant on a statistical basis. Steeper slopes often occur at the sites of rock outcroppings. Since the height of these local irregularities is often limited, they are usually considered as obstacles in trafficability analysis rather than as slopes.

Obstacles. Data on obstacle height on the seafloor are extremely limited. The few data which are available (usually in the form of bottom photographs or side scan sonar records) show a wide variation in obstacle height. For the vast majority of the seafloor (perhaps 98%) the maximum obstacle height which a vehicle would have to surmount is of the order of 6 inches or less. If the vehicle mission is such that it cannot choose its own route (to avoid larger obstacles) then the controlling maximum obstacle height may be larger (of the order of several feet and even larger in some areas). In the vicinity of steep slopes or rock outcrops, the obstacles will be larger.

Bottom Currents. Bottom currents can impose a fairly large drag force (proportional to the current velocity squared) on a seafloor vehicle. The highest velocity currents usually occur in shallower water, near the surface, and in the vicinity of topographic features such as bay entrances, between islands or near a seamount. Current velocity usually decreases near the seafloor. A typical water velocity in the deeper ocean within a few feet of the seafloor is much less than 0.1 knot (0.17 ft/sec or 5.1 cm/sec). Typical maximum values of current velocity are estimated as follows:

$<$ 0.2 knots for 75% of the seafloor
$<$ 0.5 knots for 20% of the seafloor
$>$ 0.5 knots for 5% of the seafloor

It should be emphasized that these are maximum velocities, and may be seen only once per tidal cycle, during storms, or during less frequent phenomenon. In the case of drag forces on a vehicle, it may be more realistic to design for drag forces associated with currents which more commonly prevail rather than the extreme event.

Applicable Mobility Criteria

As outlined in the preceding section, the running gear system must be designed for optimum performance in an extremely weak cohesive soil environment. Secondary considerations are for small obstacle negotiation, performance on sandy and more competent soils, resistance to small drag force due to current, maintenance of mobility and development of small drawbar forces, and satisfactory performance at very low effective ground pressures. The preceding combination of requirements based on typical environmental operating conditions and mission requirements suggests that the running gear system should be designed primarily for solving the soft soil mobility problem. Numerous running gear types have been investigated in the past; however, the need to design a practical operating system together with the requirements listed above, dictates that the running gear system be either a wheel, track, or rotor/screw system.

For a given vehicle size, a tracked system can develop at least twice the ground contact area as a wheel system even when the latter category includes rologons and similar low ground pressure configurations. For extreme cases such as the one in this study where extremely low ground pressures are of interest, wheel systems can achieve a maximum ground contact area equal to about 25% of the vehicle's planeform area. In comparison, track systems can achieve about 55% where skid steering is used or an even larger percentage where articulated systems are used to accomplish steering. While wheels do offer a better stress distribution in the soil beneath the running gear in terms of developing mobility and drawbar force, this is only a 5%-kind of advantage and is overwhelmed by the differences outlined above. Thus, the wheel is eliminated from further consideration for the running gear module.

Track systems designed for use on extremely weak cohesive soils must minimize any stress concentrations under road wheels. This is accomplished by using a larger number of smaller road wheels or by going to a skid plate or similar device such as that used on the CEL Equipment Chassis Test Track. A compliant track system is to be avoided because this leads to stress concentrations. For a track system designed for skid steering the ratio of the total track length to the track gauge or distance between the centerlines of the two track units, must be less than 1.2 to1.8. If articulated frame steering is used, ratios up to 5 have been used successfully.

Experience and design criteria for rotors (also called screws, Marsh screws, or Archimedean screws) are much more limited. Rotors do perform quite well in extremely weak cohesive soils. Experience of the Army Engineers at WES indicates that it is virtually impossible to immobilize a vehicle equipped with properly designed rotors. If the soil is so weak as to not be capable of supporting the vehicle, the rotors simply sink in a little further and function as propellers in a more viscous muddy water. The one disadvantage of the rotor configuration is that it does require a larger amount of power than a track designed for similar operating conditions. Individuals experienced in the field generally suggest that approximately twice the power is required for a rotor as for a properly designed track. It is generally assumed that a rotor will churn up the soil more than

a similarly sized track; however at slow speeds and at the extremely low ground pressures of interest in this study, this difference may not be significant. The reason for this difference in the amount of soil churning or remolding caused by the two running gears is illustrated in Figure 4. For the cases illustrated in this figure (which are not unfortunately, completely comparable) it can be seen that the track develops its maximum drawbar at a much lower slip than does the rotor system. It can also be seen in this figure that for the rotor as weaker soils are encountered, the amount of slip needed to mobilize a given drawbar force increases. The information presented on Figure 4 also points out the fact that the drawbar developed by a rotor system is available even at 100% slip, whereas with a track system in weak cohesive soils, the available drawbar begins to drop off as 100% slip is approached. This is the result of the track causing major remolding of the soil which, in a practical situation generally results in the track burying itself and becoming immobilized.

Mobility analysis for a vehicle is usually done in terms of assessing a Vehicle Cone Index ($VCI_x$) for either one pass (x = 1) which is roughly equivalent to reconnaissance work, or for multiple passes such as would occur at an operational site and may be typified as a 50-pass condition (x = 50). Once these criteria for performance characteristics are assigned to a vehicle, the soil strength characteristics at a site are evaluated in terms of a Cone Index or Rating Cone Index which is equal to the in-situ Cone Index multiplied by the Remolding Index (RI) of the soil which is comparable to the soil's sensitivity. In order for a vehicle to maintain mobility at a site, the Rating Cone Index at the critical soil depth at the site must be equal to, or greater than, the Vehicle's Cone Index for the number of passes of interest. Using this approach, the drawbar force available from a vehicle at a particular site is a function of the excess of soil strength over that required for the vehicle to maintain mobility. This is usually calculated as the difference between the Cone Index of the soil and the Vehicle Cone Index. The assigned/calculated values of Vehicle Cone Index for a number of vehicles designed for use on marshy areas and evaluated by the Army Engineers are listed in Table 7. A typical curve for predicting drawbar pull in terms of excess Rating Cone Index is shown in Figure 5. The data presented in Table 7 is presented in a slightly different format in Figure 6. Examination of these latter two figures and the table show that even for these vehicles, which were being considered for use on dredge spoils, ground contact pressures and Vehicle Cone Index ratios are fairly high compared to the conditions of interest of this study.

Most of the data points discussed above and in the referenced figures and table are calculated rather than measured data points. These have been calculated using empirical relationships derived primarily from vehicles operating at higher ground contact pressures. There is a technical need to validate the quantitative accuracy of applying these relationships in this very low ground contact pressure regime. Analysis of data from the RUM vehicle and from the CEL

Equipment Chassis Test Track at very low ground pressures suggests that for track systems designed for these very weak soils and low contact pressures, significant drawbar pull can be developed. A quick analysis of these data suggests that for a track system with a ground contact pressure well below that causing excessive sinkage, drawbar force per unit of contact area is approximately equal to 1.4 to 1.6 times the remolded shear strength of the underlying soil. These conclusions are based on tests on seafloor soils with undrained shear strength as low as 0.2 psi.

It should be pointed out that a cohesive soils Cone Index (CI) is roughly equivalent to ten times the undrained shear strength or vane shear strength of a cohesive soil. The Rating Cone Index (RCI) is roughly equivalent to ten times the remolded strength of a cohesive soil.

## CONCEPT DEVELOPMENT

Based on an analysis of the information summarized in the preceding sections, it was concluded that the module would use either a continuous belt-type track running gear system with a non-compliant suspension system, or a rotor/screw running gear system. These two approaches are pictured in Figures 7 and 8, which are not to scale and which generally show the running gear slightly oversized relative to its host vehicle. The powered running gear system would be designed as a dedicated module to be attached to its host vehicle when needed. It would utilize the host vehicle's existing power and control capabilities, and would be designed for electrical, hydraulic, and mechanical compatibility with the host vehicle. It is assumed that the module will have an in-water weight somewhere between 0 and 1,000 pounds. This weight will be minimized by the use of lightweight materials and added buoyancy if required. It was initially assumed that some in-water weight would be required in order to realize the required drawbar force. Most of the known potential host vehicles have an upward directed thruster which could be used to increase the vehicle systems effective vertical weight. Most of these thrusters (in the 5 to 10 horsepower range) can develop between 230 and 490 pounds of thrust depending upon their size, configuration, orientation and efficiency. It was assumed that a drawbar force capability of the order of 400 pounds would be needed for many of the missions envisioned.

A typical case for examining the requirements for the vehicle's resistance to forces is the lateral force on the vehicle due to a cross-current. Using a value of 0.3 knots (or 0.51 feet-per-second) as a typical maximum current velocity in the deep ocean, a cross-sectional area of 108 square feet for the vehicle with running gear module attached, and a drag coefficient of 2.0, gives a current drag force of 56 pounds. For these conservative assumptions, a cross-current velocity of 0.8 knots is needed to develop a drag force of the order of 400 pounds.

The case which requires the largest in-water weight would be where the vehicle operates on sand. In order to develop the required

400 pounds of drawbar force, the vehicle would likely need an effective negative buoyancy of 800 pounds. Assuming 200 pounds from an upward-directed thruster, the in-water weight would have to be a minimum of 600 pounds in this situation. On cohesive soils the required effective in-water weight will likely be much less, and it appears possible to use a neutrally buoyant vehicle with an upward-directed thruster developing all of the required effective negative buoyancy in order to develop the drawbar force. When the vehicle is in a "parked" mode, it is expected that it will be capable of resisting lateral forces of the order of one-and-a-half times the drawbar force it is capable of developing, in other words of the order of 600 pounds. This latter estimate assumes the same effective bearing pressure or negative buoyancy as for the example case for drawbar force outlined above.

A preliminary design for each of the two running gear concepts was roughed out assuming a near worst case soil condition, an undrained shear strength of 0.3 psi, a sensitivity of 3 and a remolded strength of 0.1 psi. For the two-track vehicle assuming an effective load of 500 pounds on each track, a 20-inch wide by 75-inch long (ground contact dimensions) track was selected. This configuration has a factor of safety of 1.5 against excessive sinkage assuming total remolding of the soil--thus, the true factor of safety is higher. Calculations indicate that this configuration will develop a drawbar force of 200 pounds per track for a total of 400 pounds for the vehicle. Each track will require approximately 5 horsepower for a speed of 15 feet-per-minute. The latter was based on experience and test measurements with the Equipment Chassis Test Track vehicle at CEL.

A preliminary configuration for a rotor/screw concept was developed using information provided by Ehrlich and Dugoff (1965). For weak cohesive soils a helix angle of $30^{\circ}$ to $40^{\circ}$ is recommended with a maximum blade height of 3 inches. The center of gravity for loading of the rotors should be at midpoint or just aft of midpoint. Since this vehicle is designed to operate equally well in either direction the center of loading should be at the midpoint of the rotor. For the soil conditions and the loading conditions given above for the track, a rotor size of 13 inches in diameter by 78 inches in length was selected. This is the soil contact length which is approximately at the quarter height, total rotor length would be of the order of 90 inches. This configuration will require approximately 9 horsepower and will provide a drawbar force approaching 400 pounds for the entire vehicle based on empirical and theoretical data presented by Ehrlich and Dugoff (1965) and by Green and Rula (1977).

## Technical Considerations

The major technical considerations which impact the development of this running gear module fall into the following five categories: (a) quantification of work capability enhancement afforded by use of this running gear module; (b) likely mission profiles for this module used with host vehicle in the future, including site characteristics;

(c) operating range for environmental conditions such as current velocity, soil strength and obstacle height; (d) mobility prediction on extremely weak cohesive soils; and (e) physical constraints on the running gear module imposed by the host vehicle and its handling system. These five categories are discussed in more detail in the following paragraphs.

A number of existing seafloor vehicles have fairly advanced work capabilities in terms of very sophisticated manipulators and tool suites. The major advantage of a running gear module would be to enhance these existing work capabilities primarily in terms of providing a better reaction, controlled movements over longer distances, and constant indexing of vehicle position on the seafloor. Specific examples of work enhancement include the following: (a) reaction for tools and elimination of the need for use of grabbers; (b) ability to pull or drag small objects out of the way; (c) provision of a reaction for a water jet or similar device for clearing buried objects; (d) ability to drag a net through an area to pick up or clear debris; (e) maintenance of position in a cross-current; (f) ability to move an object to a precise position;(g) ability to provide a moving reaction as may be required for a trenching device or similar mechanism; and (h) ability to maintain a precise moving position as may be required for site survey activities or work in an area of limited visibility near hazardous objects.

Likely future mission profiles for the running gear module are important because they help to define the types of sites at which the module would actually be used and also to define important performance characteristics that would be required. Mission profiles are hard to predict because they are a combination of needs and capabilities which tend to be somewhat a function of one another. Mission profiles can probably best be developed by analyses of the following: (a) Navy requirements for seafloor work capabilities in terms of site evaluation, construction, salvage, and search and recovery; (b) case histories of Navy seafloor operations which would have been made possible or made more efficient by the use of an operational running gear module; and (c) the work capability expected from a running gear module as summarized in the paragraph above. Analyses in the first two areas will likely give the best idea of the types of sites, and thus the environmental conditions, at which the module would be expected to operate.

The running gear module was originally conceived for use on the deep ocean seafloor. In general, this region is covered by weak cohesive soils. While better data do exist on the geotechnical properties of these soils, terra-mechanic properties are needed in order to properly design the running gear system. The performance of running gear systems of the scale being considered here is controlled by the soil properties in the upper one or two feet of the soil profile. Both undisturbed and remolded soil strengths are of interest, and the latter is more directly related to running gear performance. In addition, several investigators of trafficability for the deep ocean mining interests have suggested that a property they called "stickiness" has a major influence on the ability of the running gear to continue performing satisfactorily. This property is assumed to be related to the plasticity of the soils or

to their Bingham shear strengths. In addition to the soil characteristics, environmental conditions which impact mobility include typical slopes and obstacle height which must also be investigated and characterized in terms of expected operating conditions.

The prediction of the actual mobility performance of such a running gear module on these extremely weak and cohesive soils is a fourth technical problem area. The vast majority of all mobility studies in the off road environment are for soils with a strength of at least 2 pound-per-square-inch. There are very few studies on soils with a strength below 1 pound-per-square-inch. A major study of such weak soils has been underway by the Army Engineers who have been examining mobility on dredge spoil materials. However, most of their work has dealt with the extrapolation of existing mobility models into the region of much weaker soil strength. Very little of their effort reported to date was directed toward actual measurement of mobility performance of these extremely low ground pressure vehicles. Some physical validation of these empirical models at extremely low bearing pressures on weak soils is required along with some investigation of this "stickiness" problem in order to determine the extent of any likely adverse impact on expected running gear module performance.

The last area of major technical considerations is that of physical constraints on the module configuration which are imposed by its host vehicle and the handling system for the host vehicle. The first of these constraints is handling on the deck and over the side of the ship of the host vehicle with the module attached. The in-air weight of the module as well as its physical dimensions as they extend beyond the original dimensions of the host vehicle are important and should be minimized to reduce handling problems particularly over the side of the support ship. The second area is handling or load handling of the system in the water. If the module is designed to have a negative buoyancy, this can potentially have an adverse effect on the existing winch system and cable handling system for the host vehicle which for most vehicles would be designed to handle a nearly neutrally buoyant system. The increased mass of the vehicle with the running gear module and also the changes in its drag coefficient particularly in the vertical direction have a major impact on line dynamics and the dynamic loads seen by the handling system both in the cable and at the ship. In general, it is advisable to minimize the mass and cross-sectional area of the module in the vertical plane. The third area is constraints on available power, both electrical and hydraulic, available to the running gear module. It is assumed that the power normally used for the lateral thrusters on the host vehicle could be rewired or replumbed for use in the running gear module. This may require a switching system so that either the running gear system or the thrusters may be used during an operation on the bottom. The ability to switch from one system to the other, and/or the ability to properly control the running gear module, is dependent upon the existing control system in the host vehicle. In general, the fewer the control channels required to operate the running gear module and the simpler the

nature of these channels in terms of on/off functions as opposed to variable speed controls, the better the chances for compatibility of the running gear module with a larger range of potential host vehicles. A fourth area is operating procedures for the host vehicle. Use of the running gear module on the host vehicle will certainly change the operating procedures including handling procedures as outlined above, but perhaps more importantly, affecting how the vehicle is used on the seafloor in terms of search procedures or work procedures. This latter area also goes into work capabilities. The fact that the new configuration will elevate by about 2 feet the level of the host vehicle above the seafloor, may affect its work capabilities in terms of the positions of the existing manipulators. This could potentially adversely affect work capabilities, but it is assumed that the angle of manipulators and cameras and other related equipment can be changed to accommodate this new position and elevation of the vehicle.

Development Plans

The plans for solving the technical problems outlined above and for completing the successful development of this running gear module are summarized in Figure 9. This Technical Note is the first TN indicated under preliminary design studies. The four Purchase Order Reports (POR's) indicated under the preliminary design studies address four of the problem areas outlined above. These four studies are as follows: (a) development of mission profiles and assessment of host vehicle compatibility constraints; (b) site classification study; (c) development of mobility criteria; and (d) assessment of a running gear's enhancement of the host vehicle's work capability. The fifth major technical area listed in the preceding section and not covered extensively in the four studies listed above is that of mission profile definition. That is being covered under the item entitled Operational Analysis in Figure 9. That item is actually made up of two studies, one of case histories of Navy seafloor work and the second, a more detailed study of work enhancement and potential future missions. The other two major studies to be completed before making a final tradeoff analysis and configuration selection are an analytical study and a laboratory scale model study. The analytical study is basically an adaptation of the STAM computer model (which was developed under a separate effort for analysis of trafficability and stability of a vehicle in the surfzone) including its modification for application to the deep ocean work vehicle situation. The model studies are to be a more detailed series of physical reduced-scale tests to validate or modify the mobility criteria which are currently used and which are based on extrapolation from terrestrial experience at higher ground pressures. The remainder of the development effort is as presented in Figure 9.

## SUMMARY AND CONCLUSIONS

The information and data summarized herein indicate the following:

a) a large number of bottom-crawling vehicles have apparently performed satisfactorily on the seafloor; most are designed for more competent soil than is typical in the deep ocean; more than a third use passive/unpowered running gear; and none are an appropriate design for the objectives of this study;

b) specific data on vehicle mobility performance on deep ocean soils are very limited; however, detailed data from RUM II and the CEL Equipment Chassis Test Track indicate that mobility can be maintained and significant drawbar force developed in very weak cohesive soils typical of the deep ocean environment (a drawbar force coefficient slightly greater than the soils remolded strength is realizable even for soil strengths down to 0.2 psi, as long as bearing pressures are kept sufficiently low to prevent excessive sinkage);

c) the rotor/screw and continuous belt type track offer the best potential performance in the deep ocean environment;

d) research by the Army Engineers into mobility on dredge spoil containment areas provides some applicable performance information and an empirical framework for predicting mobility; however, most of their measurements and analyses are for soils with a higher strength than expected on the deep ocean seafloor;

e) values of environmental conditions which should be used for baseline designs in this study include a remolded strength of 0.1 psi, a sensitivity of 3, obstacle height of 6 inches, slope of 5%, and a bottom current of 0.2 knots;

f) analyses to date indicate that a module can be built which will provide about 400 pounds of drawbar pull and be capable of statically resisting larger forces on typical deep ocean cohesive soils;

g) review of current Navy vehicle missions and those for planned vehicles in the early stages of development strongly support the need for an active running gear technology which can potentially significantly enhance work capabilities in a number of circumstances;

h) two example module configurations (one utilizing a rotor/screw and the other a continuous belt type track) were designed and have in-air weights of slightly less than 2000 pounds and significantly lower in-water weights (perhaps neutrally buoyant);

i) neither module appears to impose insurmountable constraints on the host vehicle or its power, control or handling systems; and

j) while the results indicate the feasibility of this approach, several technical questions will require more refined answers or technical validation before proceeding with design and fabrication of the test module, the major question deals with the lack of any quantitative data on mobility on weak, very plastic cohesive soils at extremely low ground pressures and low speeds, and the potential effect of "stickiness" on running gear performance (a model study is suggested).

RECOMMENDATIONS

1. Since results to date support the technical feasibility and potential payoff in terms of work enhancement of the Running Gear Module, its development should be continued as outlined in the section of the report entitled, "Development Plans."

2. A model study under controlled conditions (such as those found in the laboratory) is required in order to provide the needed quantitative data on drawbar force development under extremely low contact pressures and the effect of "stickiness" of high plasticity clays on the performance of candidate running gear types. Full-scale field tests would likely be too expensive to perform and too diffficult to properly control and instrument.

3. Additional study efforts are required to define in more specific detail potential work missions and work capability enhancements and to gather the additional detailed technical data and mission/schedule information needed to select the host vehicle.

4. The collection of information on, and correspondence with operators of, seafloor work vehicles must continue with emphasis on cooperation with other organizations with similar interests/efforts and the collection and analysis of more detailed performance data as it becomes available.

ACKNOWLEDGEMENTS

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Table 1. Existing Bottom-Crawling Vehicles

| Vehicle/Function | Water Depth (ft) | Weight in Air (lbs) | Running Gear Type | Sub-merged Ground Pressure (psi) | Obstacle Height (ft) | Seafloor Types | Builder/Owner | Year Built | Reference |
|---|---|---|---|---|---|---|---|---|---|
| Anderson Crawler<br>Small experimental vehicle | 200 | ~400 | two tracks | <0.5 | ~0.5 | weak mud-rock | Anderson Undersea | 68 | Wiendieck, 1970 |
| Aquatech Cable Plow<br>Cable burial | 40 | ~4,000 | skids (towed) | ? | - | sands (?) | AquaTech, Inc. | ? | Shuman, 1973 |
| Atlantic Marine Dredge Sled<br>Trench debris removal | ~40 | ? | skids (towed) | ? | - | ? | Atlantic Marine & Diving | 75 | Sea Technology, 1977 & Peer, 1977 |
| Atlas Copco ROC 601M<br>Track drill | 60 | 9,700 | two tracks | ? | ~1 | irregular rock | Atlas Copco | 70 | Thorstensson & Wiik, 1975 |
| Bell Seaplow I<br>Cable burial | 1,000 | 27,000 | four skids (towed) | 4 | - | silts & sands | Bell Telephone | 66 | Baxter & Mueser, 1971 & Anonymous, 1967 |
| Bell Seaplow II<br>Cable burial | 2,000 | 31,000 | four skids (towed) | 4.4 | - | silts & sands | Bell Telephone | 67 | Baxter & Mueser, 1971 |
| Bell Seaplow III<br>Cable burial | 2,000 | 33,000 | three skids (towed) | 2.3 | - | silts & sands | Bell Telephone | 69 | Baxter & Mueser, 1971 |
| Bell Seaplow IV<br>Cable burial | 3,000 | 40,000 | skids (towed) | ? | - | mud-sand | Bell Telephone | 75 | Cobb, 1976 |
| Bell Survey Sled<br>Cable route survey | - | large | skids (towed) | ? | - | silts & sands | Bell Telephone | 65 | Reidy, 1967 |
| Cammell Laird Vehicle<br>Diver work support | 600 | 101,000 | four wheels | 2.75 | 2.6 | mud-rock | Cammell Laird Co., Ltd. | 69 | Daniel, 1969, Cordy, 1977 |
| Cal Eastern SeaCat<br>Inspection | ? | large | two tracks | ? | ~1 | sands(?) | California Eastern Co. | ~68 | Wiendieck, 1970 |
| CEL Cable Plow<br>Cable burial | 6,000 | ~20,000 | water lubri-cated sleds | ? | ~0.5 | mud-sand | U.S. Navy | fut. | Rockwell, 1976 |
| CEL Equipment Chassis<br>Test Track | 600 | 780 | single belt-type track | 0.5-1.1 | ~0.5 | clay-sand | U.S. Navy | 70 | Nuttall, 1970 |
| CEL Surfzone Test Track<br>Surfzone work support | ~100 | ~17,000 | two tracks | <5 | 1 | silt-rock | U.S. Navy | 78 | |
| CEL Track Drill<br>Track drill | 120 | ~ 1,500 | two tracks | ? | 1 | rock | U. S. Navy | 71 | Page, 1974 |
| Comex Cable Plow<br>Cable burial | 1,000 | ~44,000 | two tracks | ? | ? | silt-sand | Comex Services | 74 | Cordy, 1977, Durand, 1978 |
| CNEXO Test Module<br>Nodule mining test vehicle | ? | 350 | two skids | 0.2 | - | weak clay | CNEXO, COB | ? | Cordy, 1977 |
| Crawl Cutter<br>Seafloor sand dredge | 100 | >50,000 | two tracks | ? | 2.5 | sand-coral | Ocean Science & Engineering | 70 | Bascom, 1970 |
| Gopher Mark II<br>Cable burial(?) | 300 | 14,500 | skids(?) | ? | - | clay-sand | Undersea Systems | ? | Anonymous, 1971 |
| Hagenuk<br>Cable burial(?) | ? | 1,100(?) | tracks | ? | ? | clay-sand | Hagenuk Gmblt Tyskland | 72 | Thorstensson & Wiik, 1975 |
| Harmstorf Crawler<br>Pipe burial | 170 | large | tracks w/skids | ? | - | sand | Harmstorf, Holland | <72 | Welte, 1972 |
| Harmstorf Hydrojet<br>Cable burial | Shallow | large | Skids w/front rollers | ? | ? | sand | Harmstorf, Holland | 77? | Pretat, 1977 |
| Harmstorf Sled<br>Cable & pipe burial | 600 | ~80,000 | wheels w/skids | ? | ? | ? | Harmstorf, Holland | 64 | Janes, 1976<br>Harmstorf & McBride, 1965 |

Table 1. Existing Bottom-Crawling Vehicles (cont.)

| Vehicle/Function | Water Depth (ft) | Weight in Air (lbs) | Running Gear Type | Sub-merged Ground Pressure (psi) | Obstacle Height (ft) | Seafloor Types | Builder/Owner | Year Built | Reference |
|---|---|---|---|---|---|---|---|---|---|
| Hitachi-JADECCO Bulldozer | 30 | 32,000 | two tracks | ? | ? | ? | Hitachi, Ltd. | 69 | Ocean Industry, 1969 |
| Hitachi-JADECCO No. 1 Bulldozer | ? | large | two tracks | ? | ? | ? | Hitachi, Ltd. | ? | JADECCO, 1970 |
| Hitachi-JADECCO No. 2 Bulldozer | 23 | 35,000 | two tracks | 0-3.6 | ? | ? | Hitachi, Ltd. | 69 | JADECCO, 1970 |
| Hitachi-JH-360 Bulldozer | 200 | 70,000 | two tracks | ? | ? | ? | Hitachi, Ltd. | 71 | Thorstensson & Wiik, 1975 |
| Hitachi Survey Vehicle Site survey vehicle | ? | large | two tracks | ? | ? | ? | Hitachi, Ltd. | ? | Ocean Industry, 1975(c) |
| Jet Barge 3 (JB-3) Pipe burial | 350-550 | very large | skids | ? | - | ? | ? | 75 | Ocean Industry, 1975(a) |
| Jet Barge 4 (JB-4) Pipe burial | 600-1000 | very large | skids | ? | - | ? | Santa Fe International | 76 | Ocean Industry, 1975(b) |
| Jetco Trencher Rock trencher | very shallow | large | two tracks(?) | ? | ? | coral-sands | Jetco, Inc. | <74 | Wadsworth, 1974 |
| Kennecott Nodule Collector Experimental nodule collection | 15,000 | 14,000 | two skids | 1.0(?) | ? | weak clay | Kennecott Exploration, Inc. | 73 | Heine & Suh, 1978 |
| Komatsu Amphibious Bulldozer Bulldozer | 10 | large | two tracks | 9.0 | ? | ? | Komatsu, Ltd. | 69 | Komatsu, 1971 |
| Komatsu Underwater Bulldozer Bulldozer/Ripper | 200 | 85,000 | two tracks | 9.5 | ? | ? | Komatsu, Ltd. | ? | Komatsu, 1971 |
| Komatsu Underwater Bulldozer Bulldozer/Ripper | ? | 75,000 | two tracks | 8.5 | ? | gravelly sand | Komatsu, Ltd. | 70 | Ocean Industry, 1970 |
| Komatsu Underwater Bulldozer Bulldozer/Ripper | ? | 93,000 | two tracks | 10.7 | ? | silty sand | Komatsu, Ltd. | ? | Komatsu, 1975 |
| Komatsu Amphibious Bulldozer Bulldozer/Ripper | 50 | 93,000 | two tracks | 8.5 | 1.6 | clay-rock | Komatsu, Ltd. | ? | Komatsu, 1971 |
| Komatsu Amphibious Bulldozer Bulldozer/Ripper | 23 | 84,000 | two tracks | 8.5 | ? | ? | Komatsu, Ltd. | 71 | Komatsu, 1971 |
| Komatsu Amphibious Bulldozer Bulldozer/Ripper | 10 | 83,000 | two tracks | 8.5 | ? | ? | Komatsu, Ltd. | 71 | Komatsu, 1971 |
| Komatsu Walking Machine Experimental, light work | 1600 | 22,000 | eight telescopic legs | ? | large | soft soil-uneven rock | Komatsu, Ltd. | 77(?) | Offshore Services, 1978 |
| Kvaerner Pipeline Dredge Pipeline burial | 1600 | 176,000 | multiple wheels | - | - | runs on pipeline | Kvaerner Brug A/S | 78 | Biberg, 1978 |
| Naucrates Search & Inspection | 600 | 8,000 | hanging slack chain | very low | >1 | mud-rock | Wilson Marine Services | 69 | Ocean Industry, 1969(a) |
| NipponT&T Cable Plow Cable burial | 130 | ? | skids(?) | ? | ? | ? | Nippon Telephone & Telegraph | 62 | Baxter & Mueser, 1971 |
| Norges Vassdrags Cable Burier Cable burial | 500 | large | four wheels | ? | ? | sand & rock | Norges Vassdrags-og Elektrisitetsvesen | 77(?) | Ocean Industry, 1978 |

Table 1. Existing Bottom-Crawling Vehicles (cont.)

| Vehicle/Function | Water Depth (ft) | Weight in Air (lbs) | Running Gear Type | Sub-merged Ground Pressure (psi) | Obstacle Height (ft) | Seafloor Types | Builder/Owner | Year Built | Reference |
|---|---|---|---|---|---|---|---|---|---|
| Oceanic Mole<br>Pipe burial | 200 | large | ? | ? | ? | clay(?) | Oceanics, Inc. | ? | Mellor, 1977 |
| Oceanic Seamole<br>Pipe burial | 600 | large | ? | ? | ? | clay(?) | Oceanics, Inc. | ? | Mellor, 1977 |
| PMTC Trencher<br>Cable burial in rock | ~80 | ~28,000 | two tracks | 3.9 | 0.5 | sand-coral | U.S. Navy | 75 | Brackett, et al, 1976 |
| Ponga Cutter Head Dredge<br>Pipe burial | 200 | very large | sled | ? | ? | clays | Saipem, Italy | ? | Mellor, 1977 |
| RJBA Plow<br>Pipeline burial | 500 | 100,000 | two large wheels | ? | 3.3 | clay | R.J. Brown & Associates | 77(?) | Ocean Industry, 1977<br>Engineering News-Record, 1977 |
| RUM I & II<br>Support of research | 6,000 | 23,000 | two tracks | 0-4.4 | ~1.5 | mud-rock | Scripps Institution |  | Congram, 1977<br>Brown, 1978 |
| Saclay Test Unit<br>Nodule mining | 17,000 | 200 | Archimedean screw | ? | ? | clay | Centre d'Etades Nuclearies | 77(?) | Cordy, 1977 |
| Seabug I<br>Pipeline inspection | 500 | 4,500 | four wheels | 1.4 | 1.3 | clay-rock | U.D.I. & P&O Lines | 77 | Cordy, 1977 |
| Sieverts Cable Plow<br>Cable burial | 60 | 24,000 | sled | ? | ? | sand-rock | Sieverts Kabelverk | 76 | Engineering News Record, 1977<br>Peer, 1977 |
| Sperman Marine Trencher<br>Cable burial | shallow | medium | ? | ? | ? | ? | Sperman Marine Construction | ? | Engineering News Record, 1975 |
| Sub Sea Oil Services B70<br>Pipeline burial/trencher | ? | large | skids on pipe | ? | ? | rides on pipeline | Sub Sea Oil Services | <71 | Santi, 1971 |
| Sub Sea Oil Services *PBM 20*<br>Pipeline burial/trencher | 700 | large | walking clamps | ? | ? | rides on pipeline | Sub Sea Oil Services | <71 | *Ocean Industry*, 1975 |
| Sub Sea Oil Services S23<br>Pipeline burial/trencher | 200 | 133,000 | skids | ? | ? | clay-rock | Sub Sea Oil Services | 69 | Santi, 1971 |
| Sub Sea Oil Services Track<br>Drill/Track drill | ? | medium | two tracks | ? | ? | rock | Sub Sea Oil Services | <71 | Santi, 1971 |
| Sumitomo Mark III<br>Cable burial | 450 | 30,000 | two sleds | ? | ? | mud-sand | Sumitomo, Yokohama | 74 | Sumitomo, 1977 |
| Sumitomo<br>SD-73/Dredger | 23 | 136,000 | two tracks | ~7.4 | ? | ? | Sumitomo Shipbuilding | 74 | Janes, 1976 |
| Sumitomo<br>Trencher/Dredge/trencher | 230 | 132,000 | two tracks | 11.0 | ? | ? | Sumitomo Shipbuilding | 73 | Ocean Industry, 1974 |
| Tango Trencher<br>Pipeline burial | 500 | 204,000 | tracks | ? | ? | clay-sand | Groupement EPM | 76(?) | Mellor, 1977 |
| Technomare TM-102<br>Dredge & pipe burial | 600 | 420,000 | two tracks | 0-4.0 | 1.5(?) | clay-rock | Technomare, Spa | 75 | Banzoli, et al, 1976 |
| Technomare TM-402<br>Pipe & cable burial | 400 | very large | two tracks | ? | ? | clay-sand | Technomare, Spa | 78 | Ocean Industry, 1978(a) |
| Tramp Prototype<br>Inspection & light work | ? | ~5,000 | six tires | 1.7-3.5(?) | large | silts-rock | Winn Technology Ltd. | 76 | Cordy, 1977 |
| Vickers Seacat<br>Cable burial | 450 | 4,000 | eight wheels | 5-10 | 0.5-1.0 | clay-sand | Vickers Oceanics | 77 | Vickers Oceanics, 1977 |

Table 2. RUM II Characteristics

| | |
|---|---|
| Weight in air | 23,000 lbs |
| Weight in water | 13,500 lbs |
| Length | 15 ft |
| Width | 8.6 ft |
| Maximum speed | 0.85 knots |
| Ground pressure | 0- 3 psi |
| Track width | 20 inches |
| Grouser height | 1 inch |
| Grouser spacing | ∿2.5 inch |
| Horsepower per track | 7.5 hp |

Table 3. RUM II Performance in La Jolla Canyon

| Track Pressure (psi) | Realized Drawbar Force (lbs) | Drawbar Coefficient (psi) | Drawbar Force / Applied Track Weight | Sinkage (in) |
|---|---|---|---|---|
| .25 | 625 | .16 | .62 | 4-6 |
| .50 | 590 | .15 | .29 | 6-8 |
| .75 | 700 | .17 | .23 | 8-10 |
| 1.00 | 475 | .12 | .12 | 8-13 |

Table 4. Unmanned Research and Commercially Available Tethered Free-Swimming Vehicles

| Model<br>Manufacturer/Owner | Length x Width (ft) | Wt(A)(lb) | Payload (lb) | Water Depth (ft)<br>Manipulators | No. Built | Vert. Thrst (lb)<br>Power Available (hp) | Xtra Cntrl Channels | Reference |
|---|---|---|---|---|---|---|---|---|
| Angus<br>Heriot-Watt Univ., Edinburgh | 6 x 4 | 850 | 44 | 1,000<br>- | 1 | (0.5hp)<br>~3.5, electric | ? | Janes, 1976 |
| Boctopus<br>BOC, Ltd, London | ? | ? | ? | 2,000<br>- | 1 | ?<br>? | ? | Given, 1978 |
| CETUS 2-01<br>ULS Marine Ltd, UK | (identical to TROV) | | | | 1 | | | Given, 1978 |
| CONSUB 1/2<br>British Aircraft Corp. | 9 x 5 | 3,024 | ? | 2,000<br>1-2 | 3 | ?<br>>20, hydraulic | ? | Janes, 1976<br>Given, 1978 |
| Cord<br>Harbor Branch Foundation, Florida | ? | small | ? | 1,500<br>? | 2 | ?<br>>7, electric | ? | Janes, 1976 |
| Cutlet<br>British Underwater Weapons Establishment | ~15 x 6 | ? | ? | ?<br>1 | 1 | ?<br>? | ? | Janes, 1976 |
| ERIC<br>D.C.A.N., France | 13 x 6 | 4,500 | 112 | 2,300<br>1-5 DOF | 1 | ~500<br>~40, electric | ? | Janes, 1976 |
| ERIC II<br>D.C.A.N., France | smaller | smaller | ? | 19,700<br>2 | 1 | yes<br>? | ? | Janes, 1976 |
| Filippo<br>Guido Gay, Italy | ? | ? | ? | 1,000<br>- | 1 | ?<br>? | ? | Given, 1978 |
| ORCA-I (SAAB-SUB)<br>SAAB -SCANIA, Sweden | 11 x 7 | ~8,800 | ? | 2,300-20,000<br>3, 6 DOF&AFFB | 1 | (30 hp)<br>70, hydraulic | ? | Janes, 1976<br>Saab, 1978 |
| RCV-150<br>Hydro Products, San Diego | 4 x 4 | 980 | >150 | 1,800-6,600<br>(opt) 1-4 DOF | 4 | >100<br>15, hydraulic | ? | Gray and Fridge, 1970<br>Hydro Products, 1978 |
| RCV-225<br>Hydro Products, San Diego | 2 x 2 | 180 | - | 1,800-6,200<br>- | 24 | (0.1 hp)<br>0.4, electric | ? | Janes, 1976 |
| RECON II<br>Perry Oceanographic, Florida | 4 x 3 | 450 | 75 | 1,500<br>1-very simple | 1 | ?<br>? | ? | Janes, 1976 |
| RECON III<br>Perry Oceanographic, Florida | 5 x 2 | 330 | 34 | 1,600<br>- | 2 | 40<br>? | ? | Perry Oceanographic, 1978 |

Table 4. Unmanned Research and Commercially Available Tethered Free-Swimming Vehicles-cont.

| Model<br>Manufacturer/Owner | Length x Width (ft) | Wt (A)(1b) | Payload (1b) | Water Depth (ft)<br>Manipulators | No. Built | Vert. Thrst (1b) | Xtra Cntrol Channels | Power Available (hp) | Reference |
|---|---|---|---|---|---|---|---|---|---|
| RECON IV<br>Perry Oceanographic, Florida | small | ? | ? | 6,000<br>1 | 1 | ? | ? | ? | Given, 1978 |
| RECON V (II)<br>Perry Oceanographic, Florida | 6 x 3 | 500 | 75 | 1,200<br>1-4DOF | 1 | Yes | Yes | ? | Perry Oceanographic, 1978 |
| Recorp MDV-A<br>Smit-Leclen, Louisiana | ? | ? | ? | 3,000 | 1 | ? | ? | ? | Given, 1978 |
| SCARAB<br>Ametek, San Diego | larger | ? | ? | 6,000<br>2 | 2 | ? | ? | ? | Given, 1978 |
| SCORPIO I<br>Ametek, San Diego | 7 x 4 | 1,500 | 350 | 3,000<br>1-5DOF | 6 | (5 hp) | yes, >3 | 17.5, hydraulic | Ametek, 1978 |
| SCORPIO II<br>Ametek, San Diego | similar | ? | ? | ?<br>2 | ? | ? | ? | ? | James, 1976 |
| Seaspy<br>U&ME, Ltd, UK | ? | ? | ? | 1,000 | 1 | ? | ? | ? | Given, 1978 |
| Snurre<br>NTNFK, Norway (Myren, Oslo) | 7 x 5 | 1,040 | ? | 1,640-2,000 | ? | 560 | ? | ~16, hydraulic | James, 1976<br>Ocean Industry, 1978(a) |
| Telenante 1,000<br>Institut Francals du Petrole | 13 x 5 | 2,420 | ? | 3,280<br>1 | 1 | (3.5 hp) | ? | ~22, hydraulic | James, 1976 |
| TELESUB 1,000<br>Remote Ocean Systems, California | ? | ? | ? | 2,000<br>- | 1 | ? | ? | ? | Given, 1978 |
| TOM 300<br>Thomson-CSF, France | 12 x 6 | 6,500 | 400 | 1,000<br>1 | 1 | Yes | ? | ? | Comex, 1978 |
| TREC<br>McElhanney/ISE | smaller | ? | ? | 1,200 | 4 | ? | ? | ? | Given, 1978 |
| TROV (SMT)<br>McElhanney Offshore/ISE, Canada (Sonar Marine, UK's modified version) | 5.5 x 3 | 800 | 150 | 1,200-1,500<br>2 | 4 | yes | ? | ? | James, 1976<br>Given, 1978 |
| UFO-300<br>Winn Technology, Ireland | ? | ? | ? | 1,000<br>? | 1 | yes | ? | ? | Given, 1978 |
| VIP<br>Ocean Systems, Virginia | 10 x 5 | 3,000 | 590 | 1,200-2,000<br>2 (4 & 7DOF) | 1 | (7 hp) | ? | <28 | Ocean Systems, 1978 |

Table 5. Potential Navy Host Vehicles

| Vehicle/Operator | Water Depth (ft) | Length x Width x Height (ft) | Weight in Air (lb) | Weight in Water (lb) | Payload Capacity (lbs) | Variable Buoyancy (lbs) | Vertical Thrust (hp) | Work Capability | Power Avail (hp) | Cntrol Channels Avail | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Unmanned Vehicles** | | | | | | | | | | | |
| CURV II - Keyport NTS Keyport, WA | (virtually identical to CURV II - NOSC vehicle) | | | | | | | | | | |
| CURV II - NOSC NOSC, Long Beach | 2,500 | 15x6x6 | 3,450 | - | 400 | - | 10 | 3 DOF Manipulator | ~30,elec | ? | Navy, 75 |
| CURV III - NOSC NOSC, San Diego | 10,000 | 15x6.5x6.5 | 4,000 | - | 2,000 | - | 10 | 3 DOF Manipulator | ~30, elec | ? | Navy, 75 |
| Deep Drone SUPSALV, Washington,DC | 2,000 | 7x4x4.5 | 1,300 | -22 | 200 | - | 3 | - | ~ 9, elec | - | Navy, 77 Janes, 76 |
| LOSS - PIV NCSL, Panama City, FL | 850 | ~18x16x10 | ? | ? | ? | ? | very large | - | very large | ? | Ocean Industry, 77(a) |
| RUWS NOSC, Hawaii | 20,000 | 11x4.5x4.8 | 7,000 | -50 | ? | ? | 125 lbs | 1-7 DOF & 1-4 DOF | ? | ? | NOSC, 76 |
| SCAT NOSC, San Diego | 2,000 | 6x2x4 | 400 | ? | 80 | ? | ? | Manipulator | ? | ? | Navy, 75 |
| Snoopy-Electric NOSC, San Diego | 1,500 | 3.4x2.2x1.5 | 150 | -1 | ~10 | - | yes | - | ? | ? | Navy, 77 |
| Snoopy-NAVFAC NAVFAC, Washington,DC | 1,500 | 3.8x2.3x2 | 300 | -1 | 10 | - | yes | - | ? | ? | Janes, 76 |
| SORD I & II NTS Keyport, WA | 6,500 | 6x4x10 | 4,000 | yes? | 7,500 | - | ? | ? | ? | ? | Navy, 75 |
| **Manned Vehicles** | | | | | | | | | | | |
| Alvin Woods Hole Oceanographic | 12,000 | 22.5x8.5x12.5 | 32,000 | ~0 | 1,000 | ? | ? | Manipulator | ~15 | ? | Navy, 75 |
| DSRV I & II (Mystic & Avalon) SUBDEVGRUONE, San Diego | 5,000 | 49.7x8.2x9.5 | 75,000 | ~0 | ~3,600 | ? | 15 hp | ? | ~45 | ? | Navy, 75 |
| NR-1 U.S. Navy | ? | 136.3x12.3x14.5 | ~800,000 | ~0 | ? | ? | ? | Manipulator | ? | ? | Janes, 73 |
| Sea Cliff SUBDEVGRUONE, San Diego | 6,500-20,000 | 26x12x12 | 48,200 | ~0 | ? | ? | ~8 | Two Manipulators | ~18 | ? | Navy, 75 Sea Technology, 78 |
| Turtle SUBDEVGRUONE, San Diego | 6,500-10,000 | 26x12x12 | 48,200 | ~0 | ? | ? | ~8 | Two Manipulators | ~18 | ? | Navy, 75 Sea Technology,78 |
| Trieste II SUBDEVGRUONE, San Diego | 20,000 | 78x15x27 | 180,000 | ~0 | ? | ? | - | Mechanical Arm | ~20 | ? | Navy, 75 |

Table 6. Percentage of the Seafloor Covered by Various Sediment Types (from Herrmann, et al, 1972)

| Type of Deposit | Percentage of Seafloor | Average Depth (feet) |
|---|---|---|
| Terrigenic | | |
| Shelf sediments | 8 | 328 |
| Muds | 18 | 6,700 |
| Pelagic | | |
| Globigerina ooze (calcareous) | 35 | 11,800 |
| Pteropod ooze (calcareous) | 1 | 6,600 |
| Diatom ooze (siliceous) | 8 | 12,800 |
| Radiolarian ooze (siliceous) | 2 | 17,400 |
| Red/brown clay | 28 | 17,700 |

Table 7. Example Characteristics and Vehicle Cone Index Ratings for Vehicles Considered for Use on Dredge Spoil (from Willoughby, 1977)

| No. | Vehicle* Description | Gross Vehicle Weight lb | Tire or Track Width in.* | Track Length in Contact Ground in.** | No. of Support Rollers in Contact with Ground | Ground Clearance in. | Gross Horse-power | Ground Contact Pressure psi | $VCI_1$ | $VCI_{50}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Amphicat | 925 | 11.5 | 38.6 | NA | 8.0 | 16 | 1.04 | 1 | 3 |
| 2 | Thiokol Trachmaster | 5,500 | 32.0 | 99.0 | 8 | 13.5 | 138 | 0.87 | 4 | 11 |
| 3 | Thiokol Spryte | 8,080 | 36.0 | 98.0 | 10 | 11.0 | 170 | 1.15 | 3 | 8 |
| 4 | M29C | 6,000 | 20.0 | 78.5 | 8 | 11.0 | 65 | 1.91 | 6 | 15 |
| 5 | MTV | 10,000 | 21.0 | 190.0 | 10 | 33.0 | 160 | 1.25 | 4 | 11 |
| 6 | Marsh Scrow Amphibian | 3,954 | 26.0 | 106.0 | NA | 20.0 | 116 | 0.72 | 1 | 5 |
| 7 | Quality Marsh Ditcher | 23,500 | 48.0 | 190.0 | 8 | 38.0 | 120 | 1.29 | 0 | 2 |
| 8 | RUC | 10,000 | 39.0 | 216.0 | NA | 49.0 | 760 | 0.59 | 0 | 0 |
| 9 | Quality Marsh Dragline | 32,000 | 60.0 | 204.0 | 8 | 38.0 | 82 | 1.31 | 0 | 2 |
| 10 | Cat D4DLGP | 20,800 | 30.0 | 87.0 | 12 | 14.0 | 75 | 3.98 | 7 | 18 |
| 11 | Cat D5LGP | 30,000 | 34.0 | 111.0 | 14 | 12.0 | 105 | 3.97 | 7 | 17 |
| 12 | John Deere 350 CWT | 12,050 | 33.0 | 69.0 | 10 | 13.0 | 46 | 2.65 | 6 | 14 |
| 13 | Case 350 HF | 9,127 | 36.0 | 63.0 | 10 | 11.0 | 44 | 2.79 | 7 | 17 |
| 14 | IH500E WT | 10,720 | 32.0 | 68.0 | 10 | 13.0 | 42 | 2.46 | 5 | 13 |
| 15 | P&H 315 | 45,000 | 30.0 | 114.0 | 16 | 20.0 | 90 | 6.58 | 10 | 25 |
| 16 | Liebherr 925 | 45,000 | 30.0 | 129.0 | 16 | 21.0 | 100 | 5.81 | 10 | 24 |
| 17 | Bucgrus Erie 15B | 31,000 | 20.0 | 108.0 | 14 | 13.0 | 95 | 7.18 | 13 | 32 |
| 18 | Bantam C451 | 33,000 | 24.0 | 120.0 | 14 | 13.0 | 108 | 5.73 | 11 | 26 |

* Rotor width or tire width projected to ground contact.
** Rotor dimensions or tire dimensions projected to ground contact.

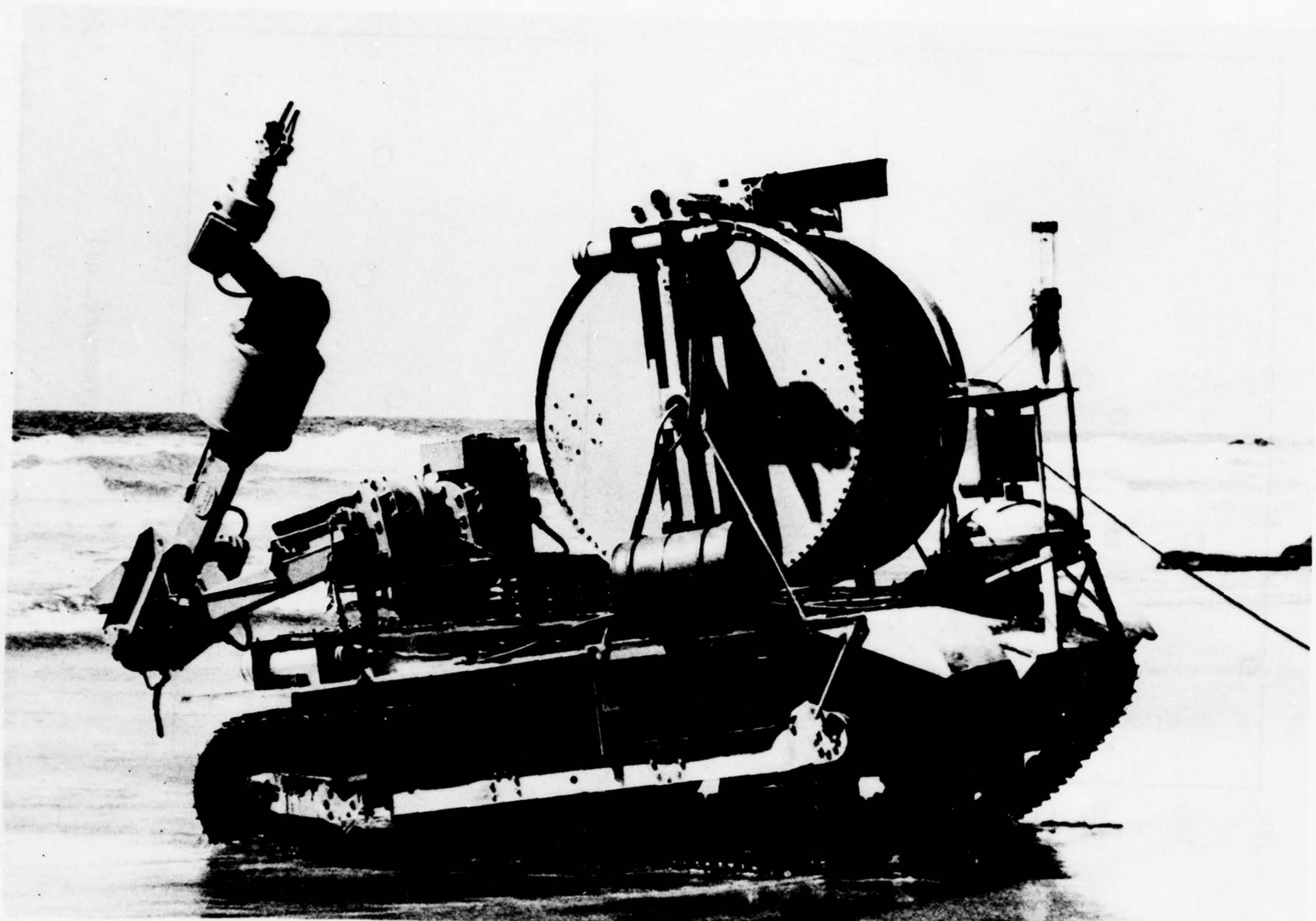
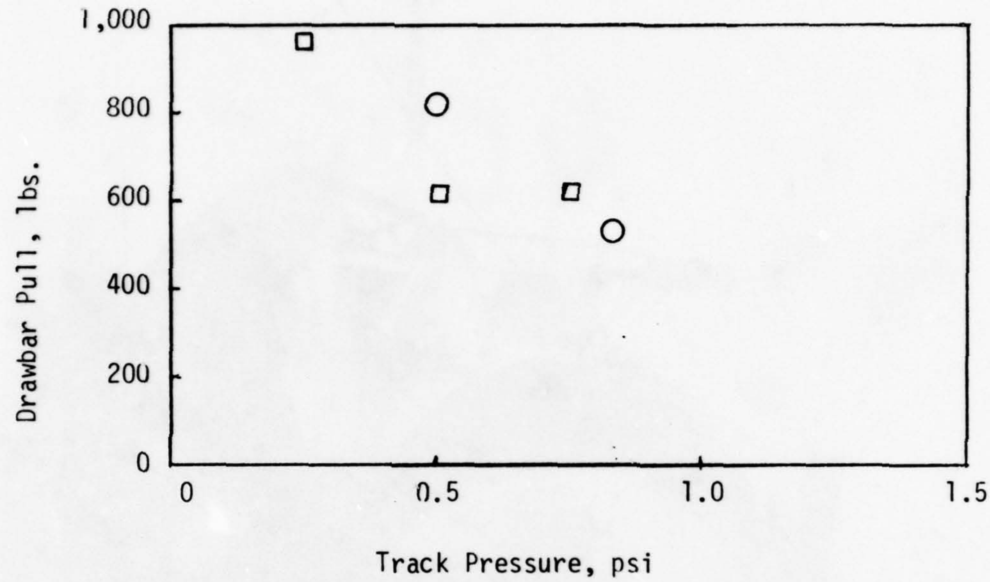


Figure 1. RUM I Vehicle as originally configured for work from the beach out in 1960.

a) Tests in La Jolla Canyon




b) Tests in San Clemente Basin and San Diego Trough

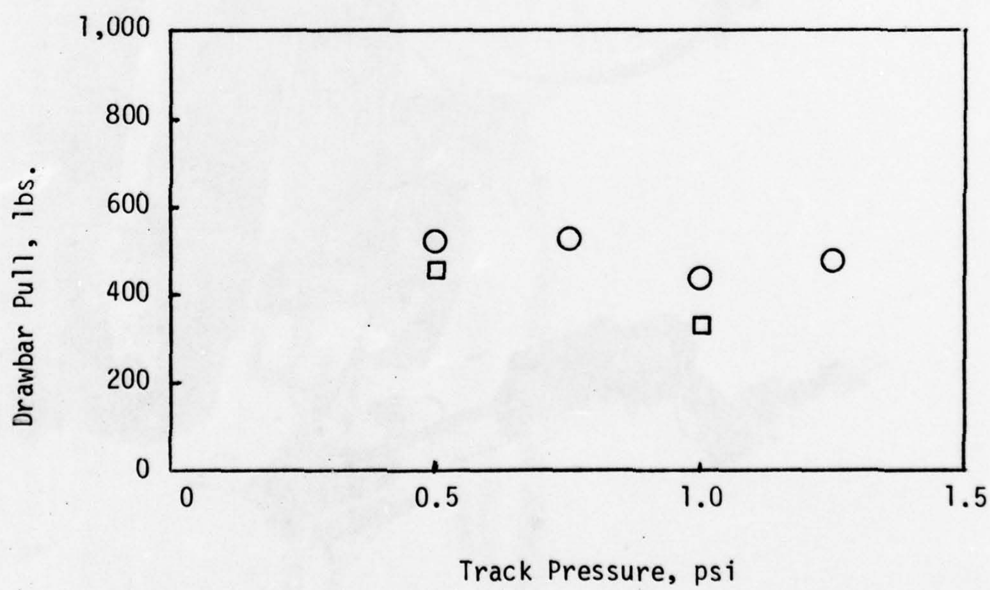



Figure 2. Performance of RUM II vehicle in several deep ocean environments (after Gibson & Anderson, 1974).

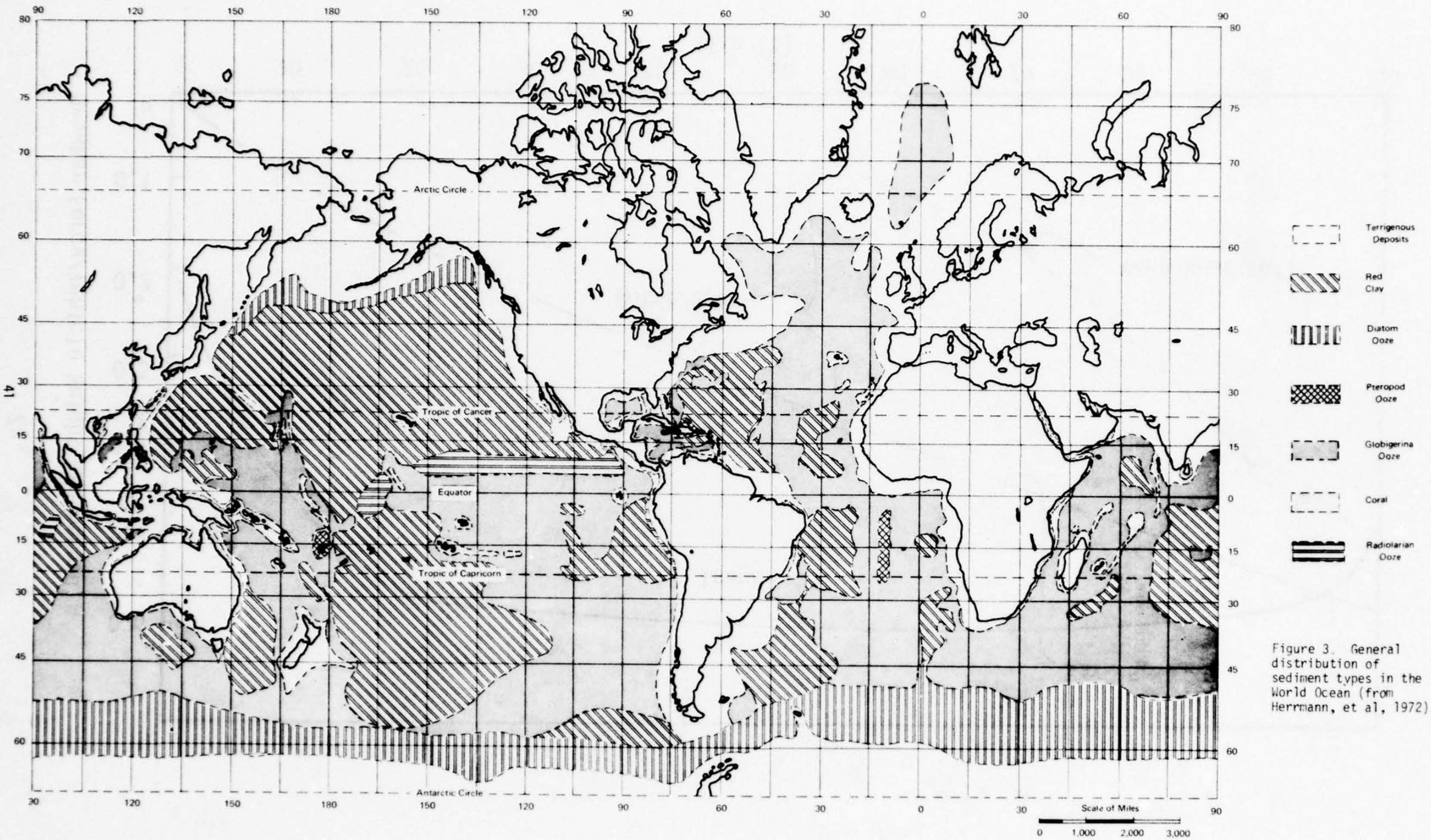



Figure 3. General distribution of sediment types in the World Ocean (from Herrmann, et al, 1972).

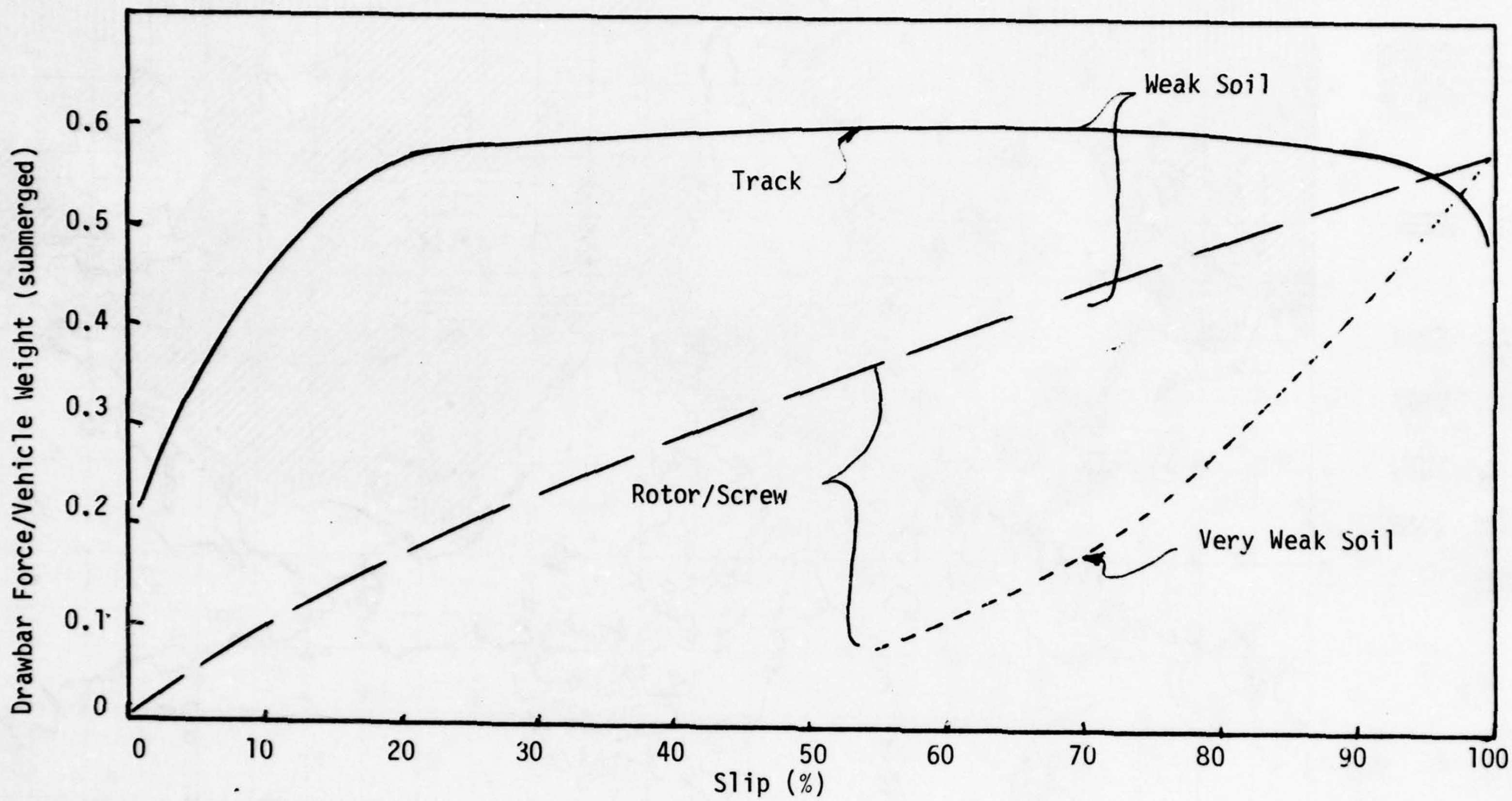



Figure 4. Running gear Performance behavior on weak cohesive soil.

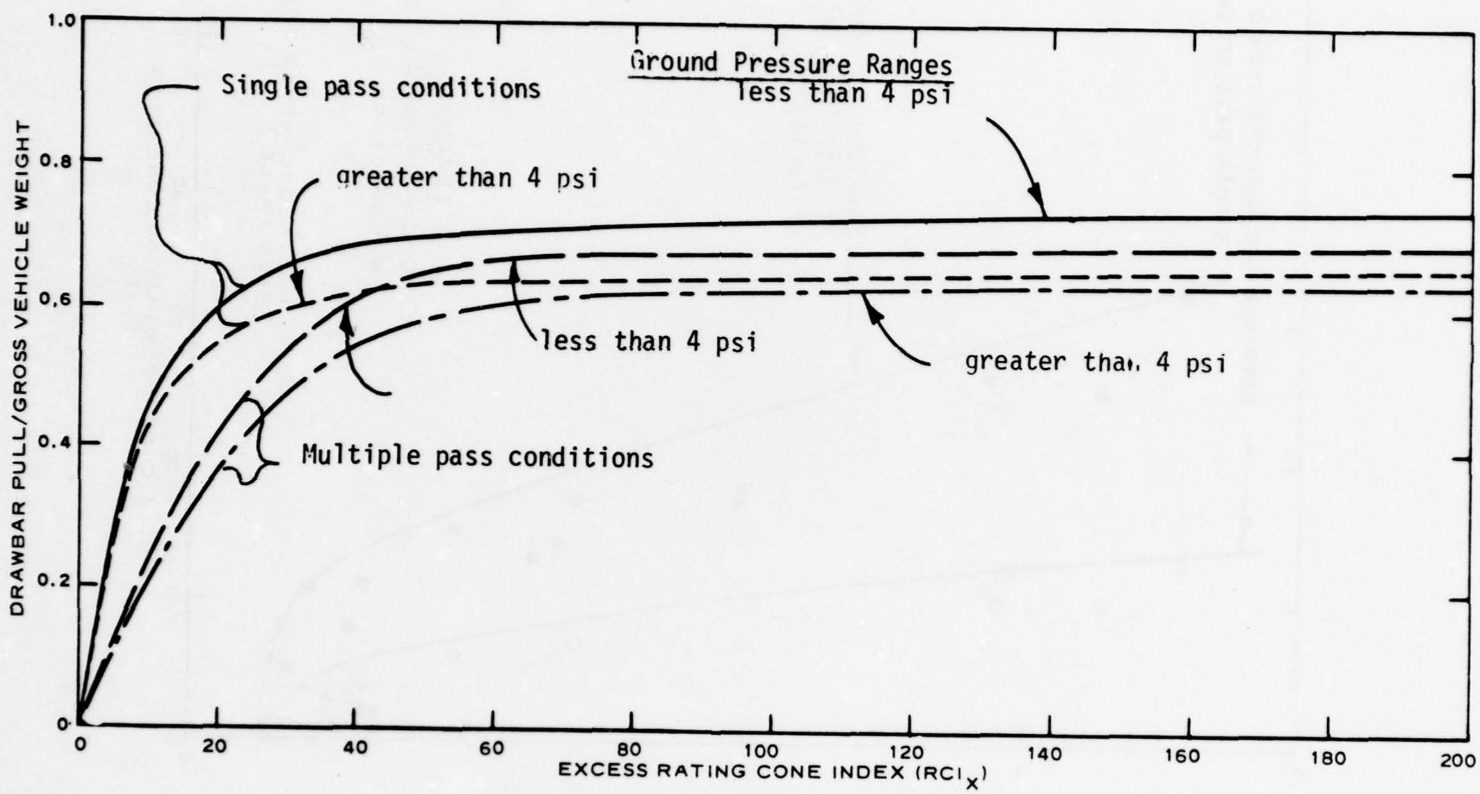



Figure 5. Predicted drawbar pull as a function of excess Rating Cone Index for tracked vehicles on fine-grained soils (from Willoughby, 1977).

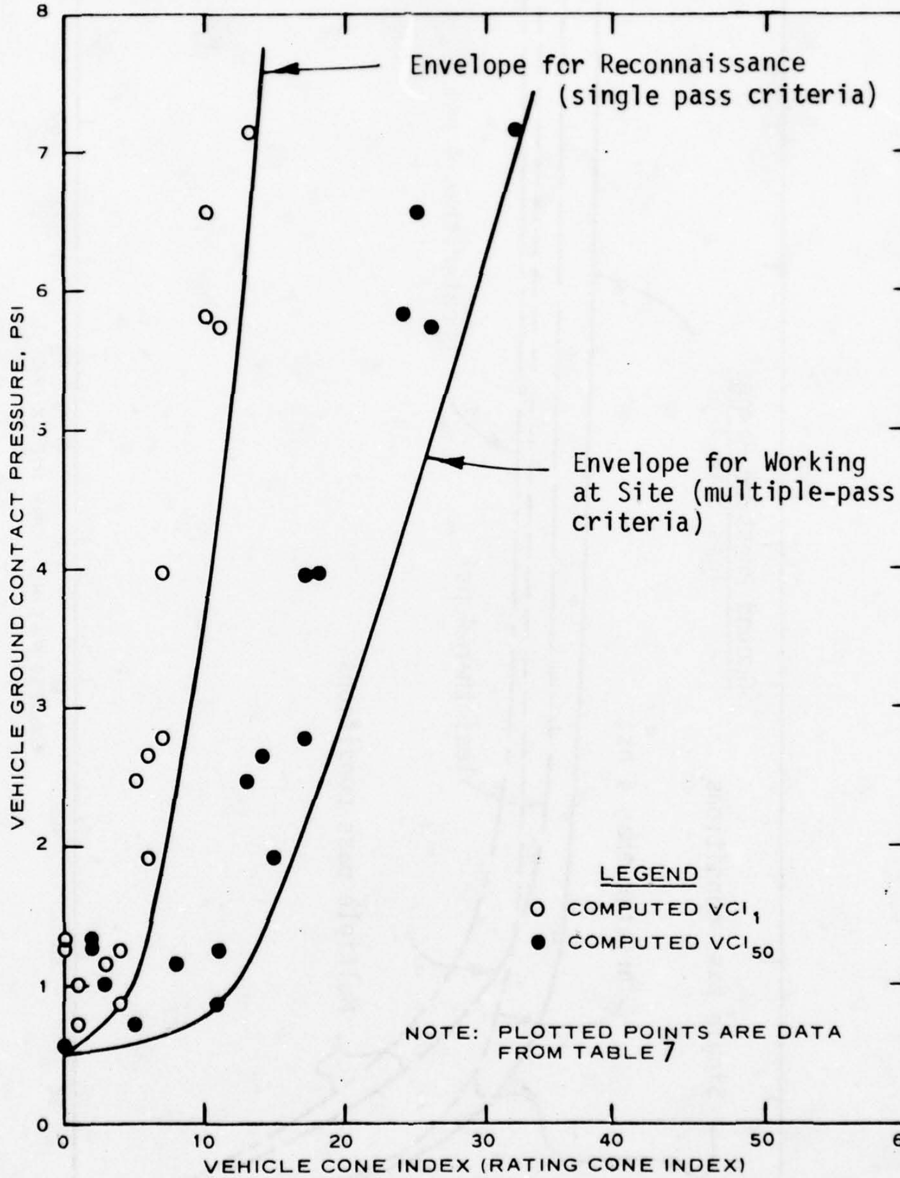



Figure 6. Example calculated mobility and performance envelopes for dredge spoil vehicles (from Willoughby, 1977).

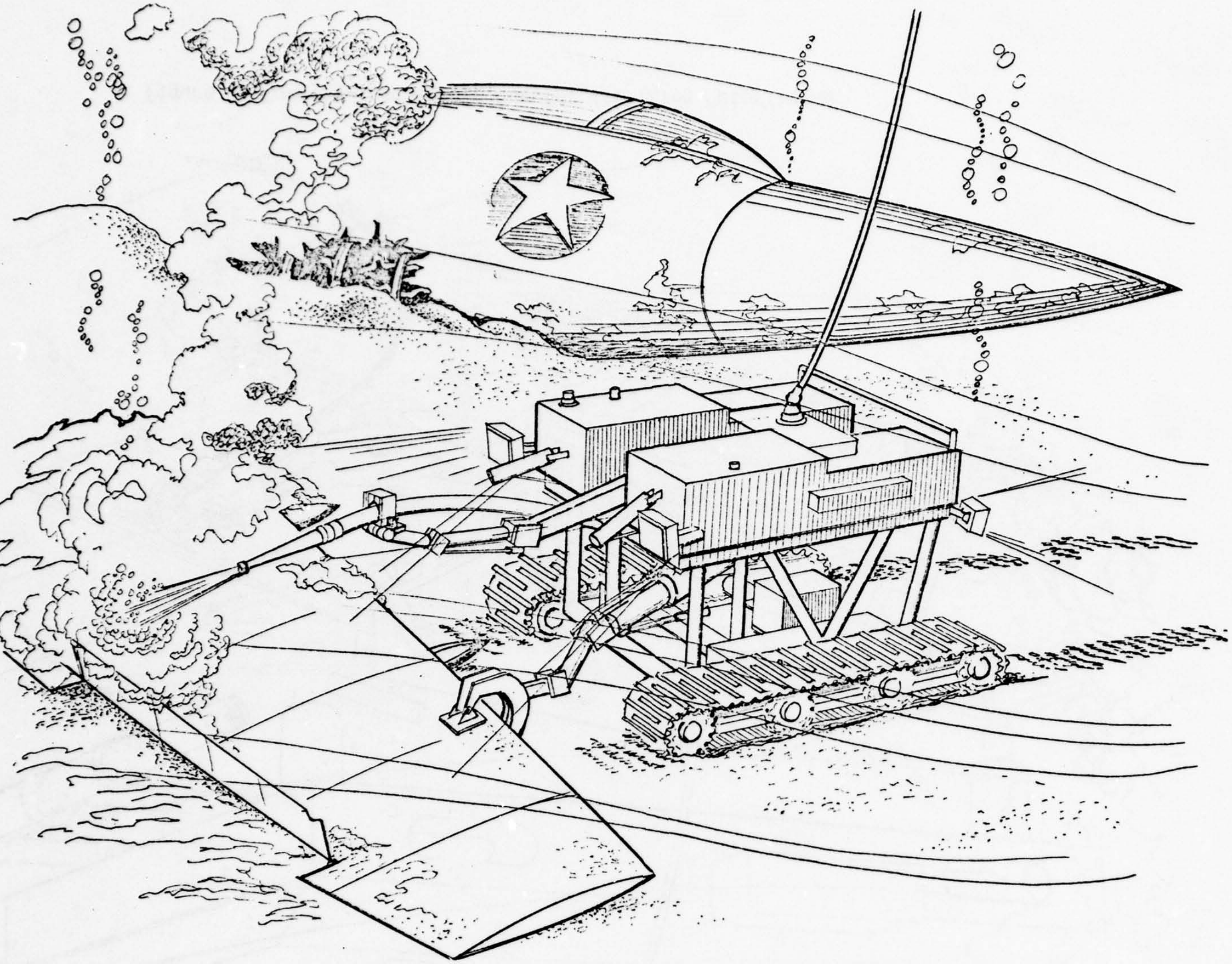


Figure 7. Running Gear Module Concept utilizing continuous belt-type track.

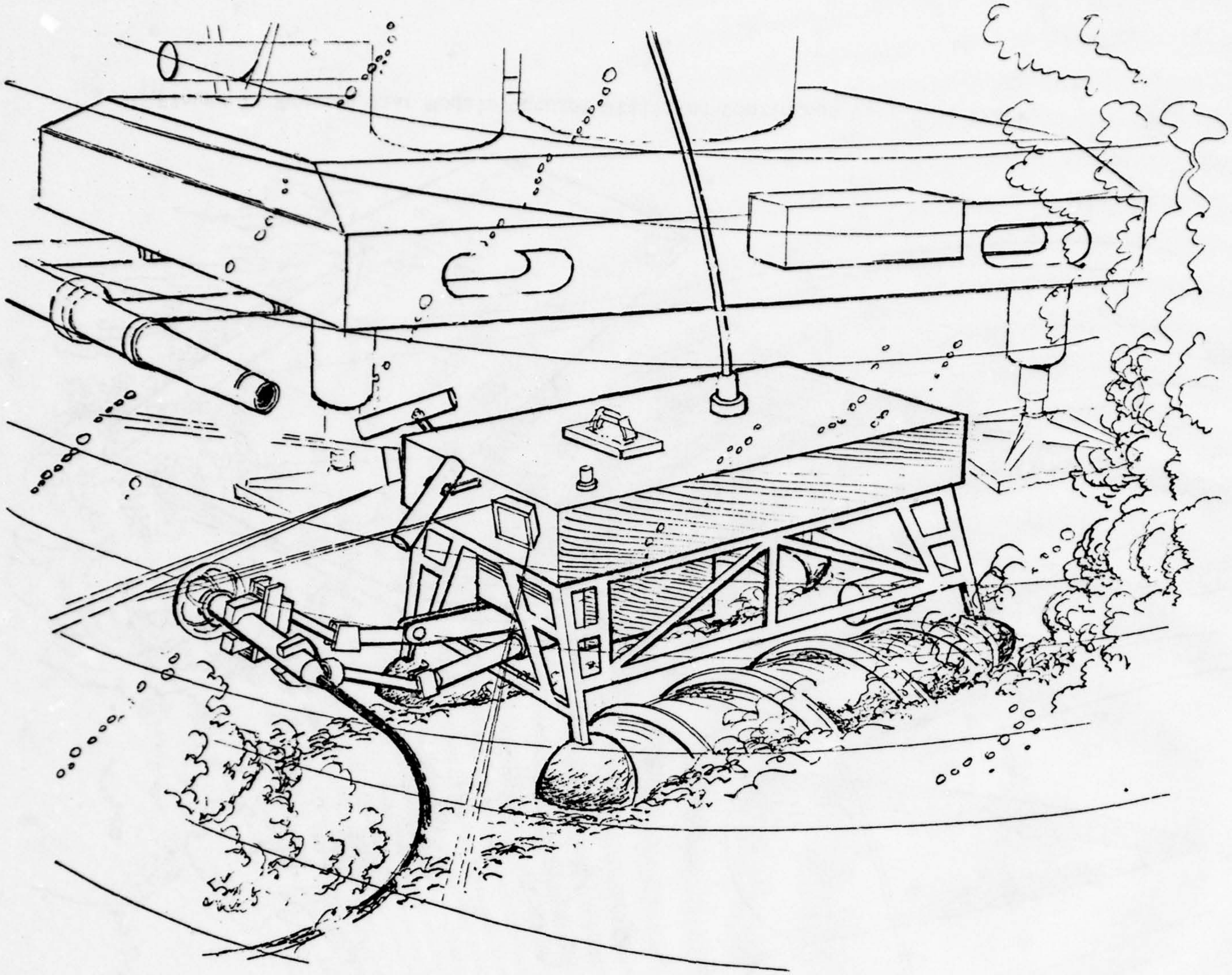
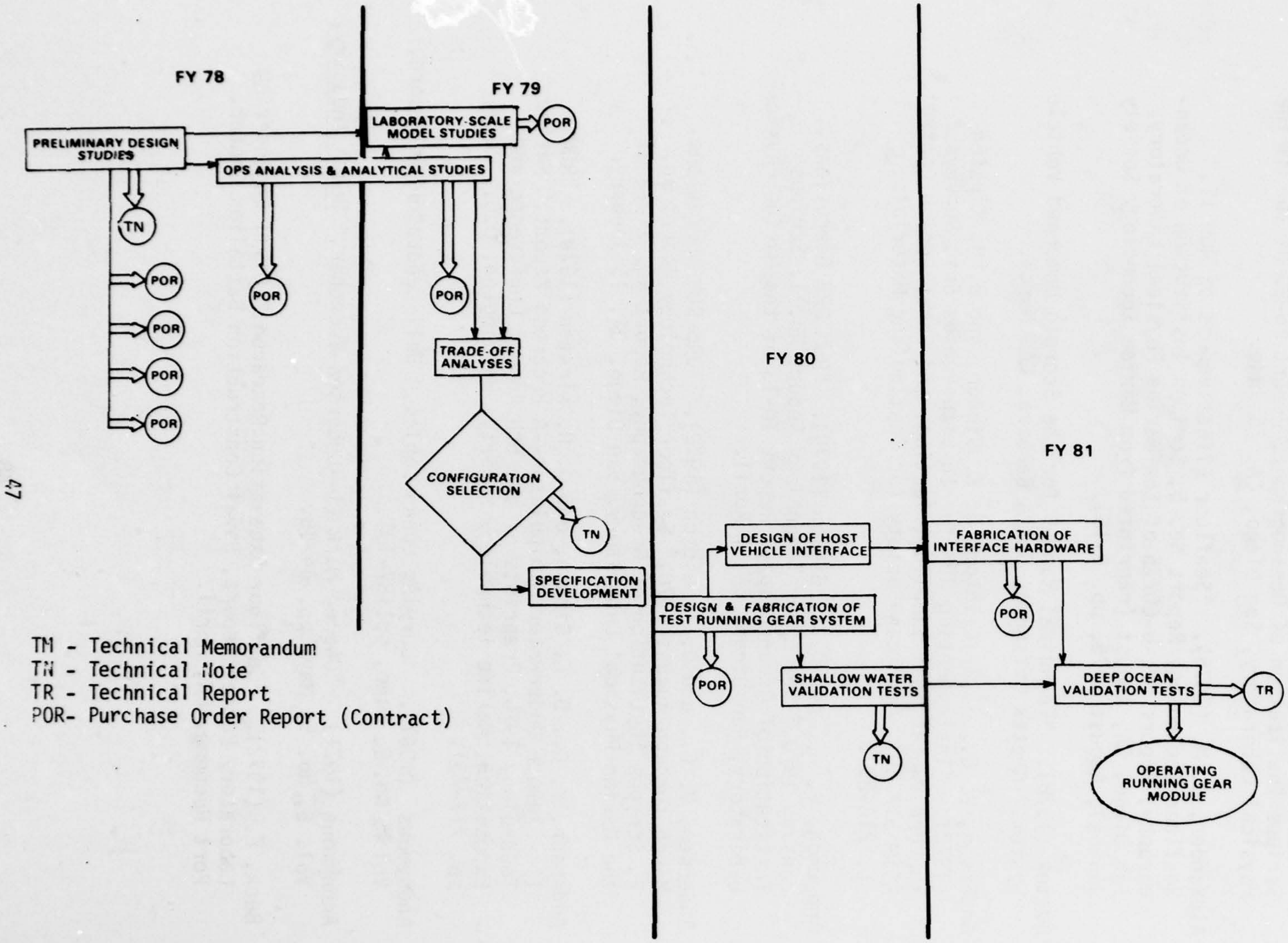


Figure 8. Running gear module concept utilizing rotor/screw.




TM - Technical Memorandum
TN - Technical Note
TR - Technical Report
POR- Purchase Order Report (Contract)

*FIGURE* 9. **DEVELOPMENT PLAN FOR DEEP OCEAN RUNNING GEAR MODULE.**

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| Multiply | By | To Obtain |
|---|---|---|
| inches | 2.54 | centimeters |
| feet | 0.3048 | meters |
| miles (U.S. statute) | 1.609344 | kilometers |
| miles (nautical) | 1.852 | kilometers |
| pounds (mass) | 0.4535924 | kilograms |
| pounds (mass) per cubic foot | 16.01846 | kilograms per cubic meter |
| pounds (force) | 4.45 | newtons |
| pounds (force) per square inch | 6894.757 | pascals |
| pounds (force) per square foot | 47.88026 | pascals |
| knots | 0.5144 | meters per second |
| feet per second | 0.3048 | meters per second |
| miles per hour | 0.4470 | meters per second |
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